Multi-messenger counterparts to gravitational waves

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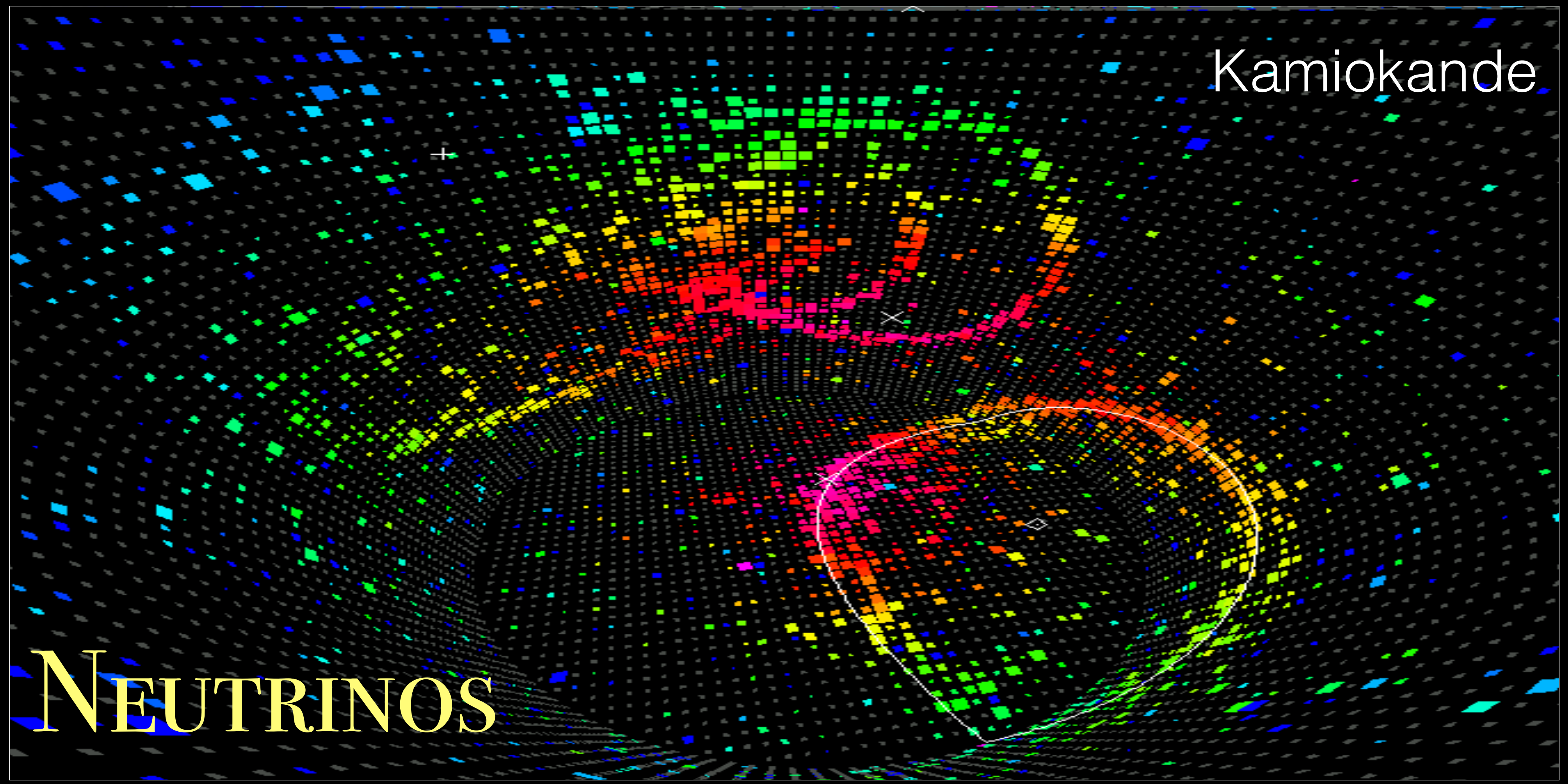
Gravitational wave sources

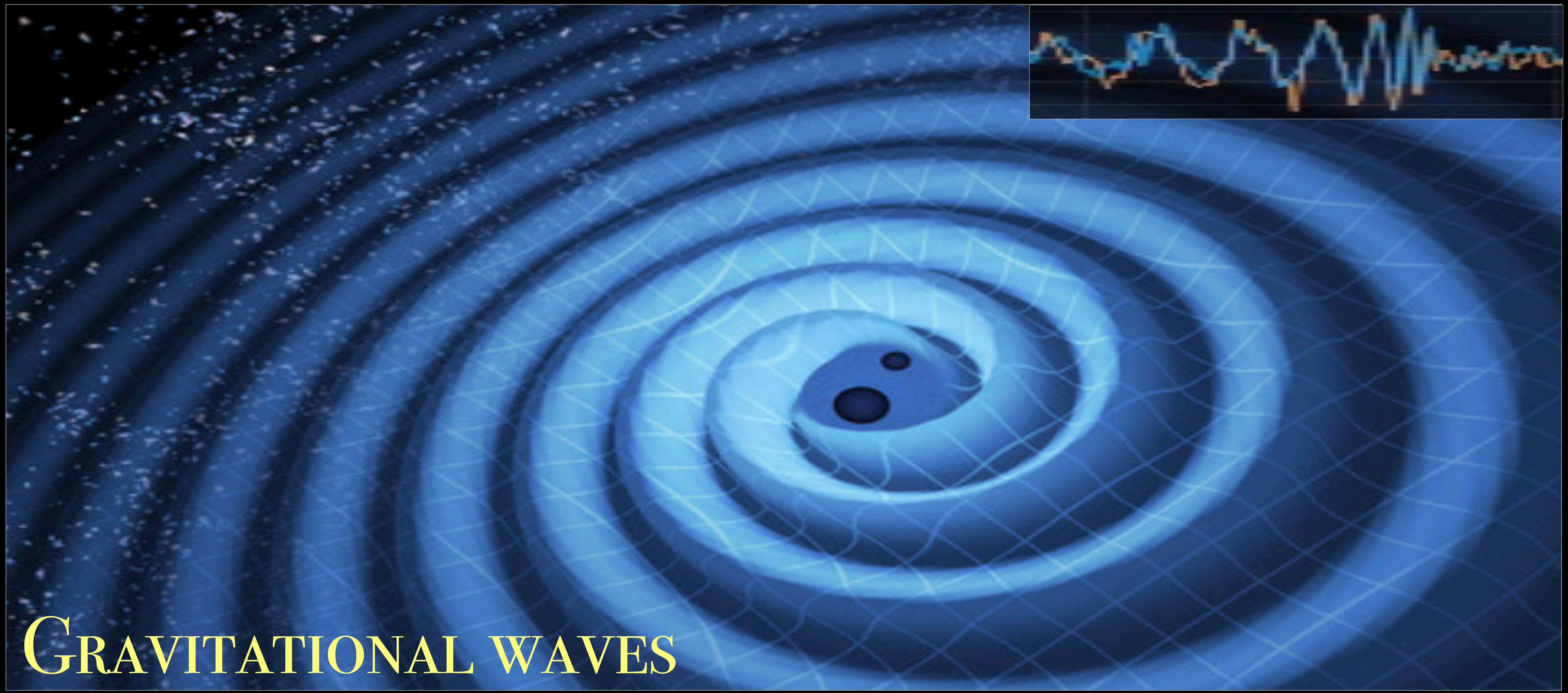
Electromagnetic and particle counterparts

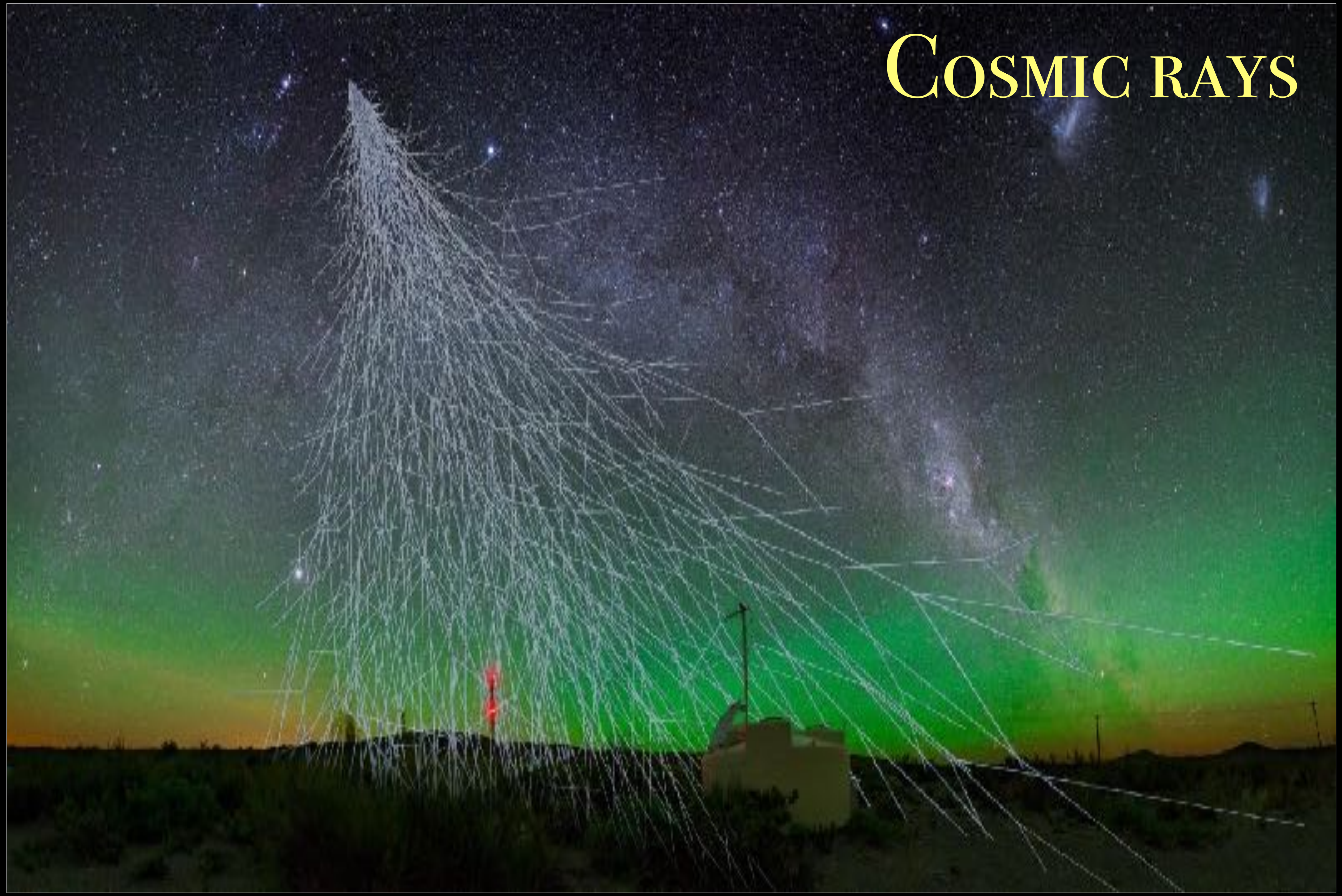
- Signatures from stellar compact object binaries
- Signatures from single stellar collapse – r-process in collapsar jets
- Signatures from BBH in accretion disks
- Signatures from extreme mass ratio inspirals
- Signatures from MBH/SMBH binaries

What next?

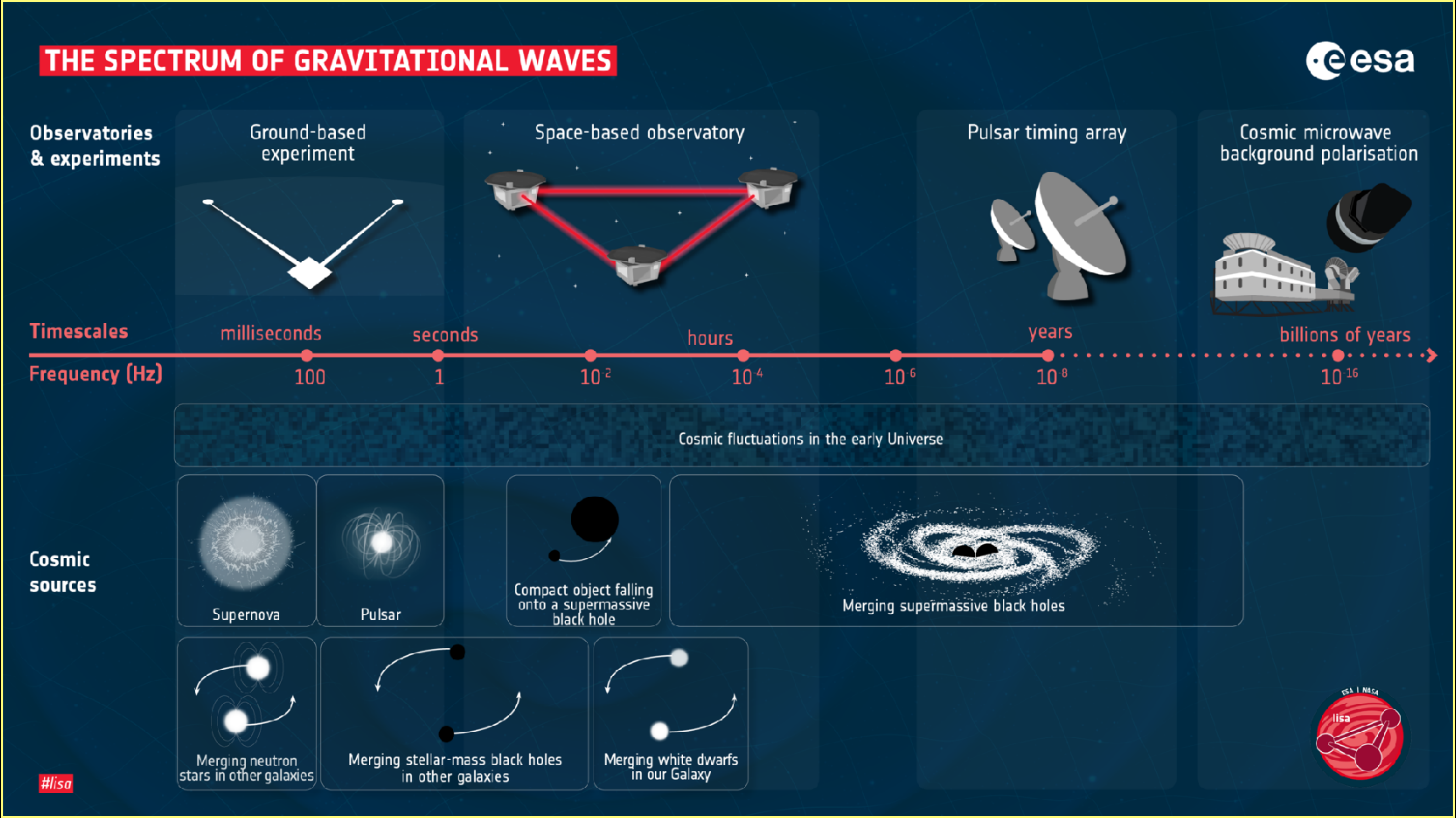
Multi-messenger astronomy



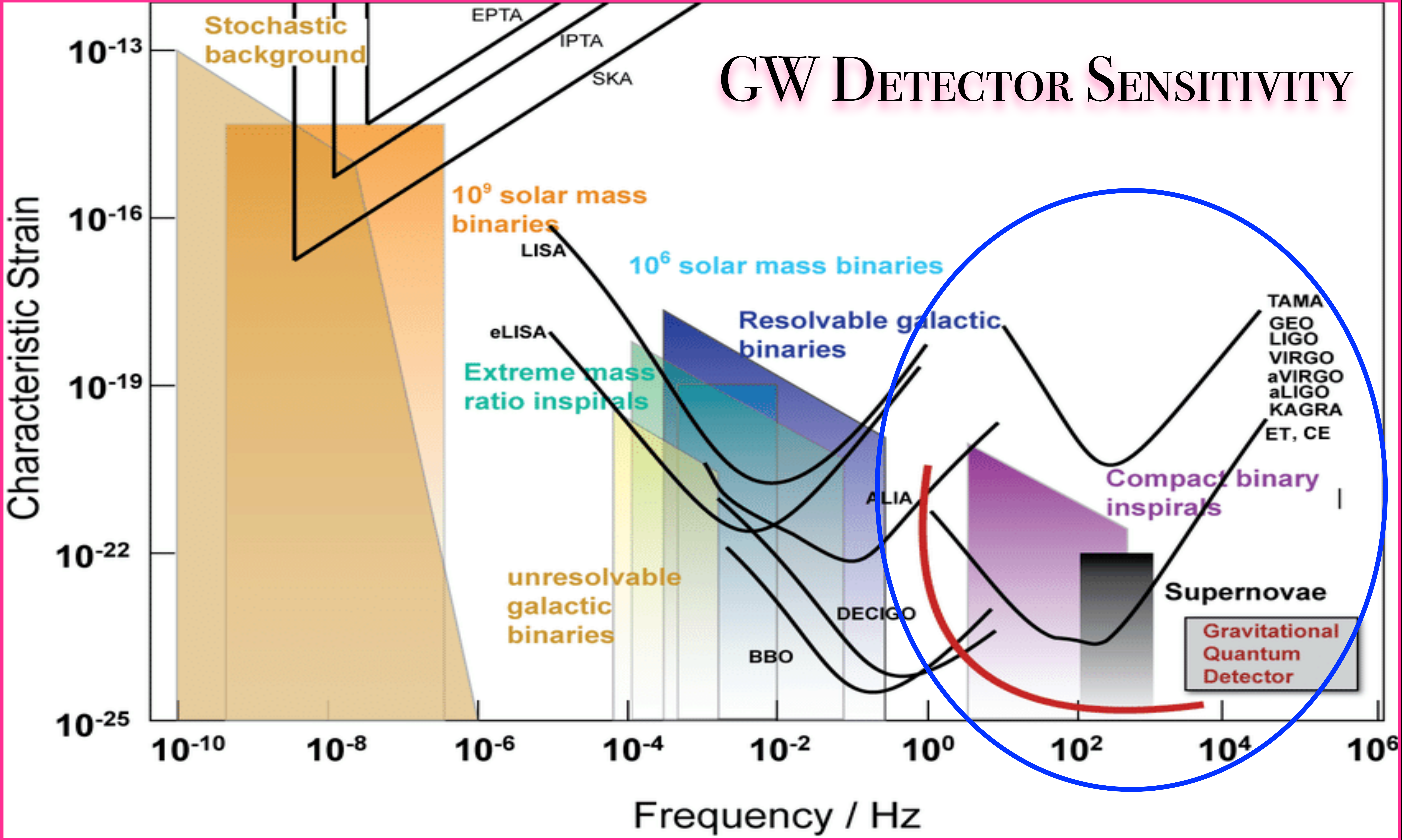




Gravitational wave sources



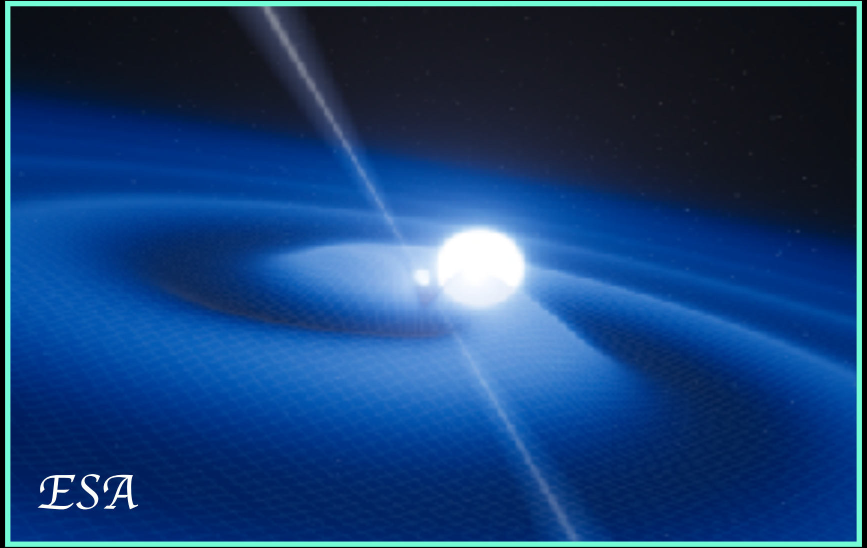
GW Detector Sensitivity



Compact object mergers

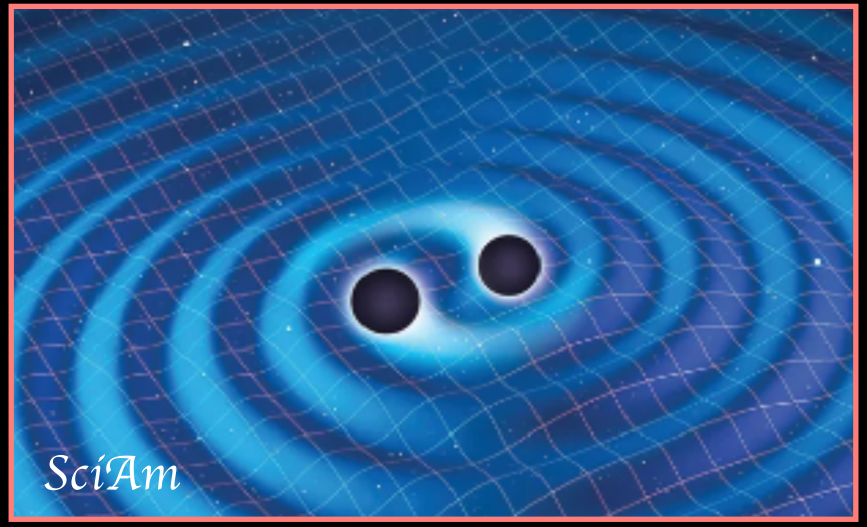
Double neutron star

Neutron star-Black hole

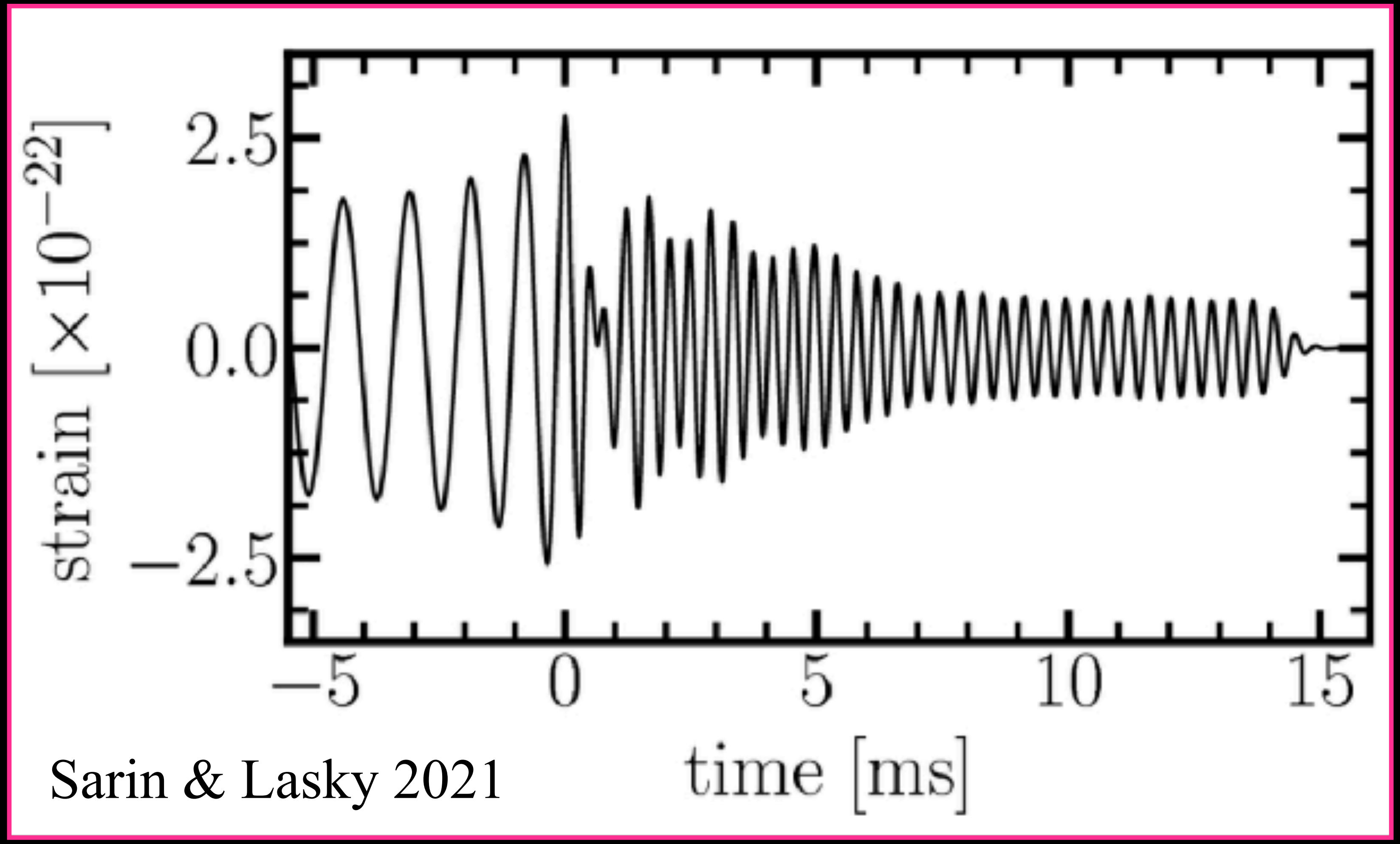


Neutron star-white dwarf

White dwarf-Black hole



Double black hole



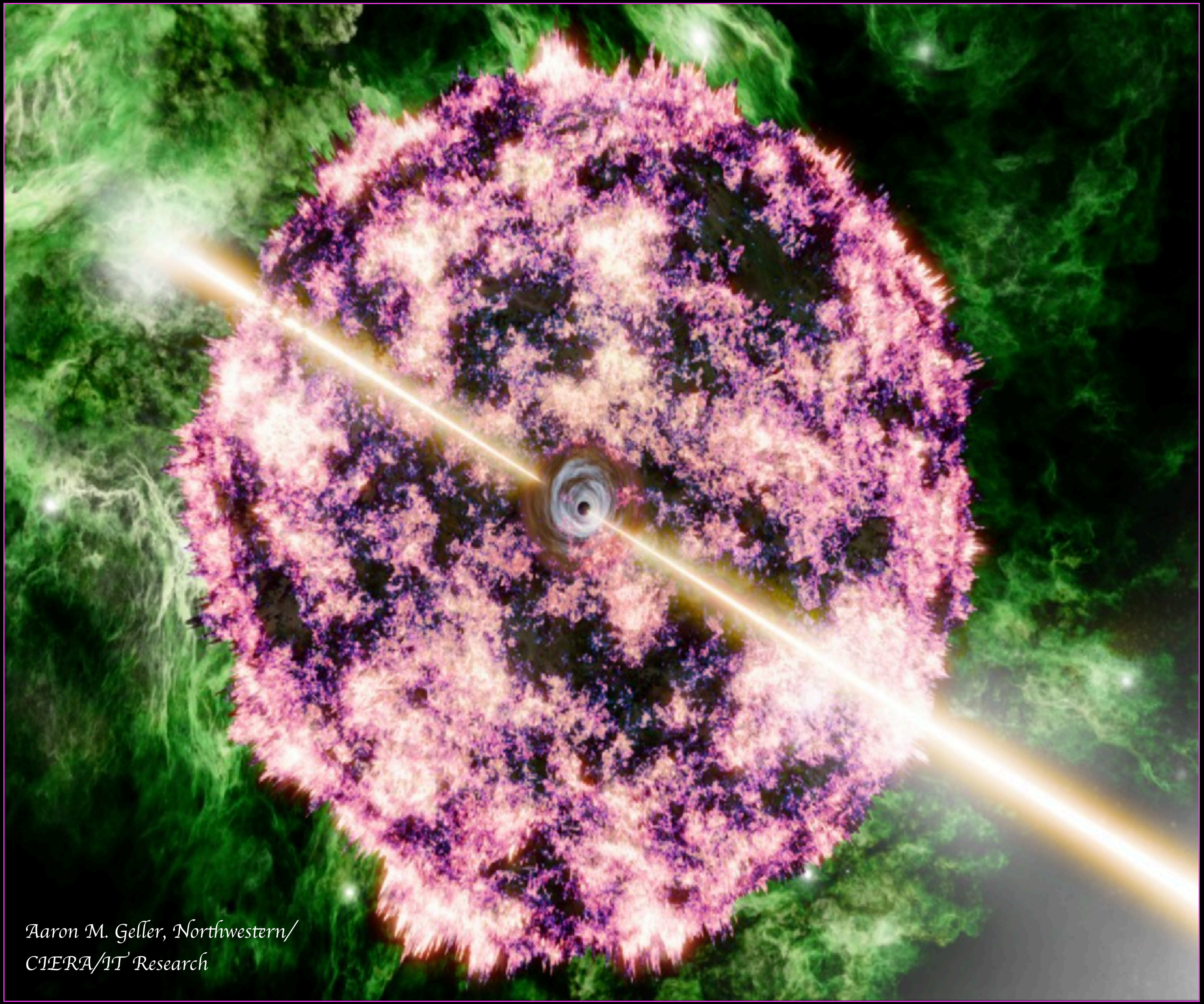
Short gamma-ray burst

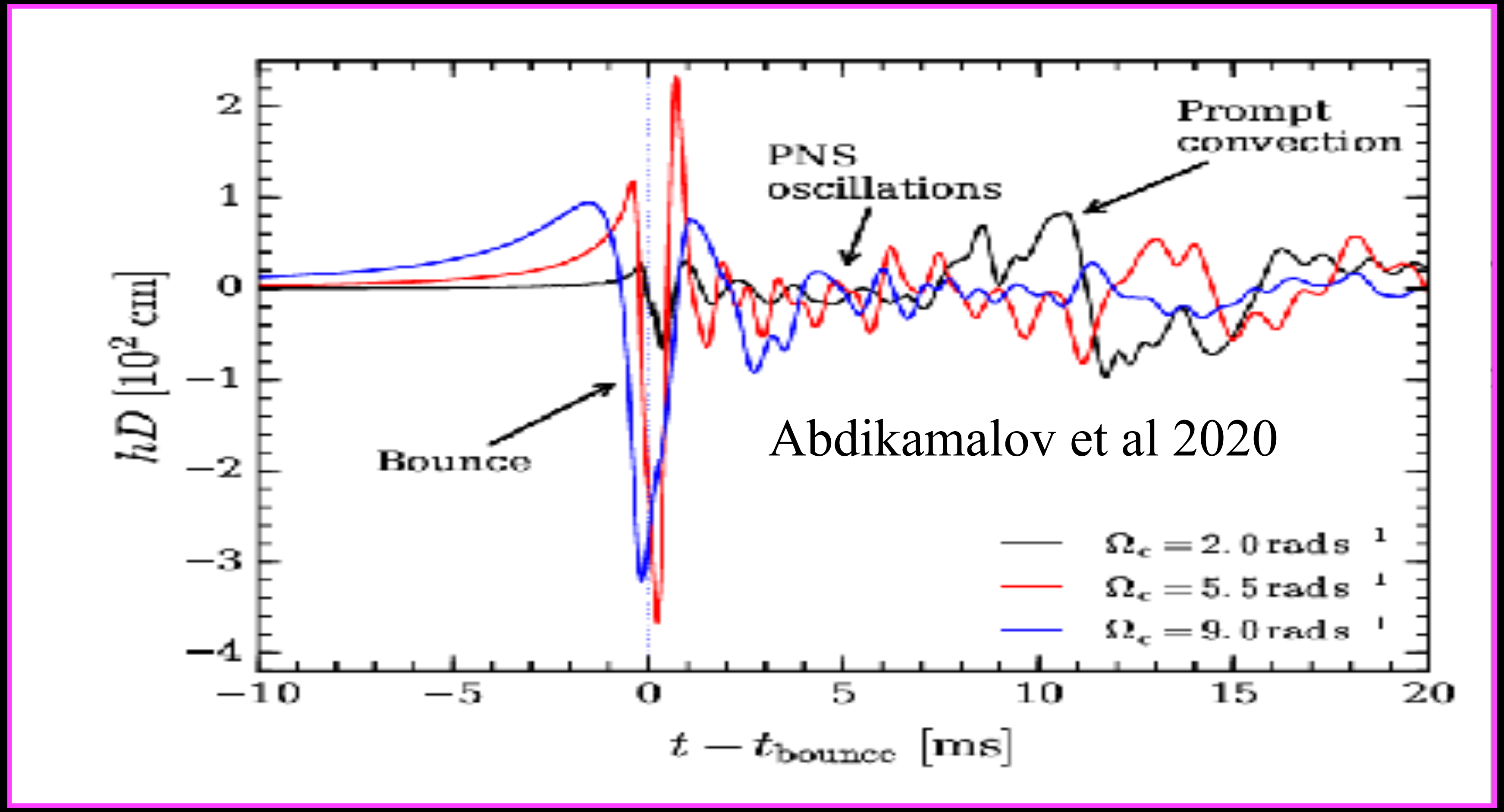
Long gamma-ray burst

Low lum. gamma-ray burst

Peculiar transient

Massive star collapse





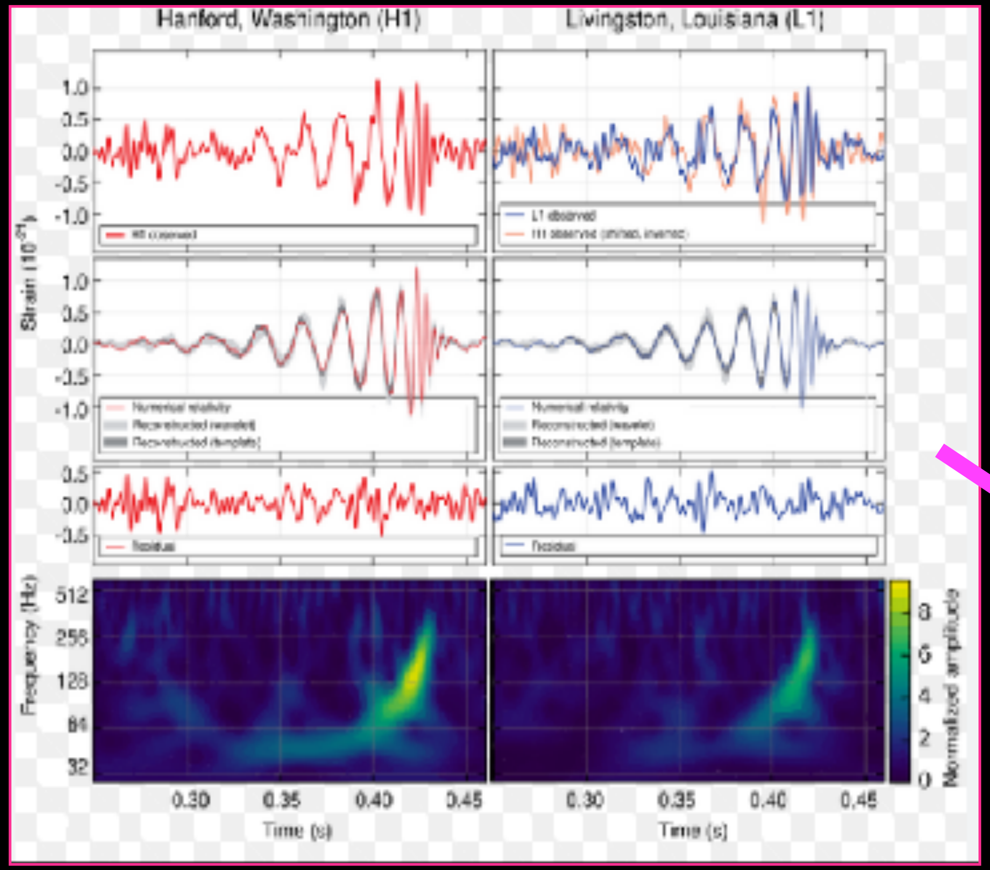
Supernova

Long gamma-ray burst

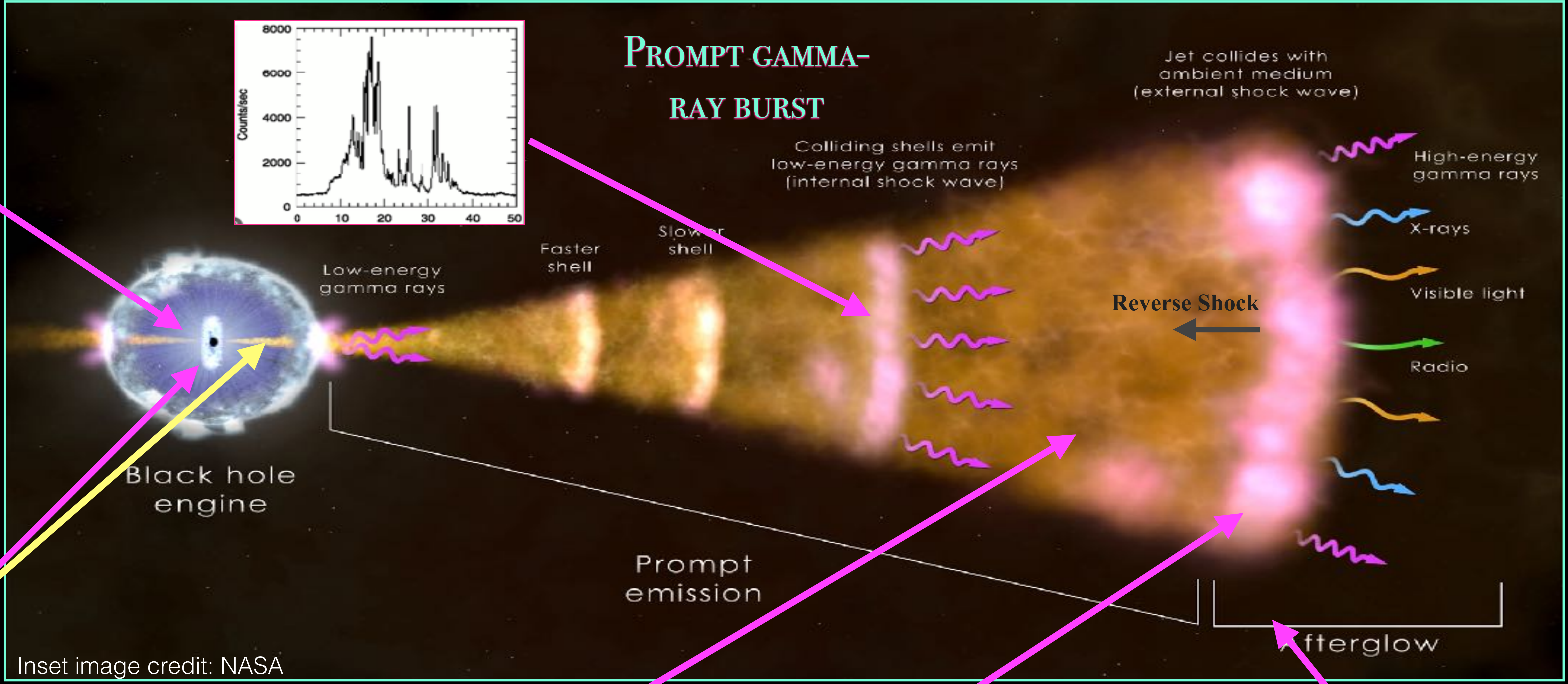
Short gamma-ray burst

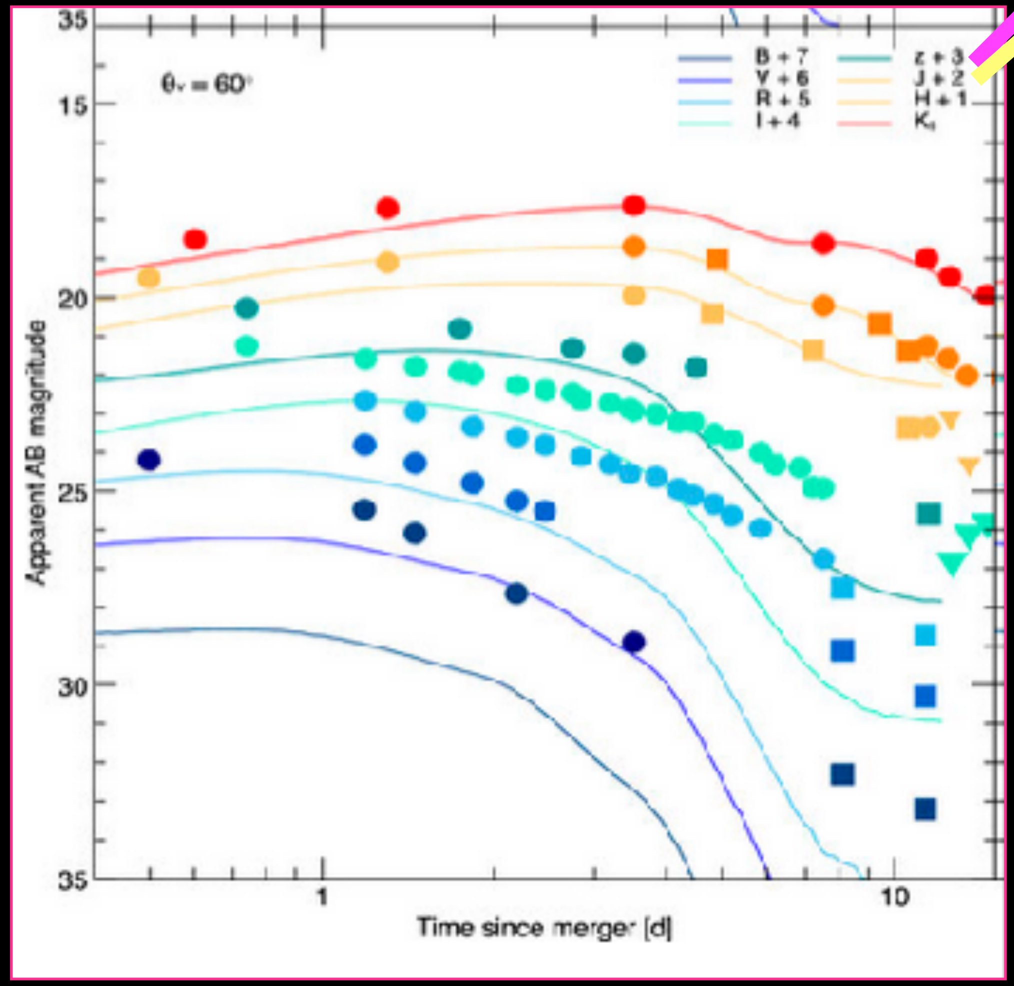
Kilonova from

R-process in GRB jets!



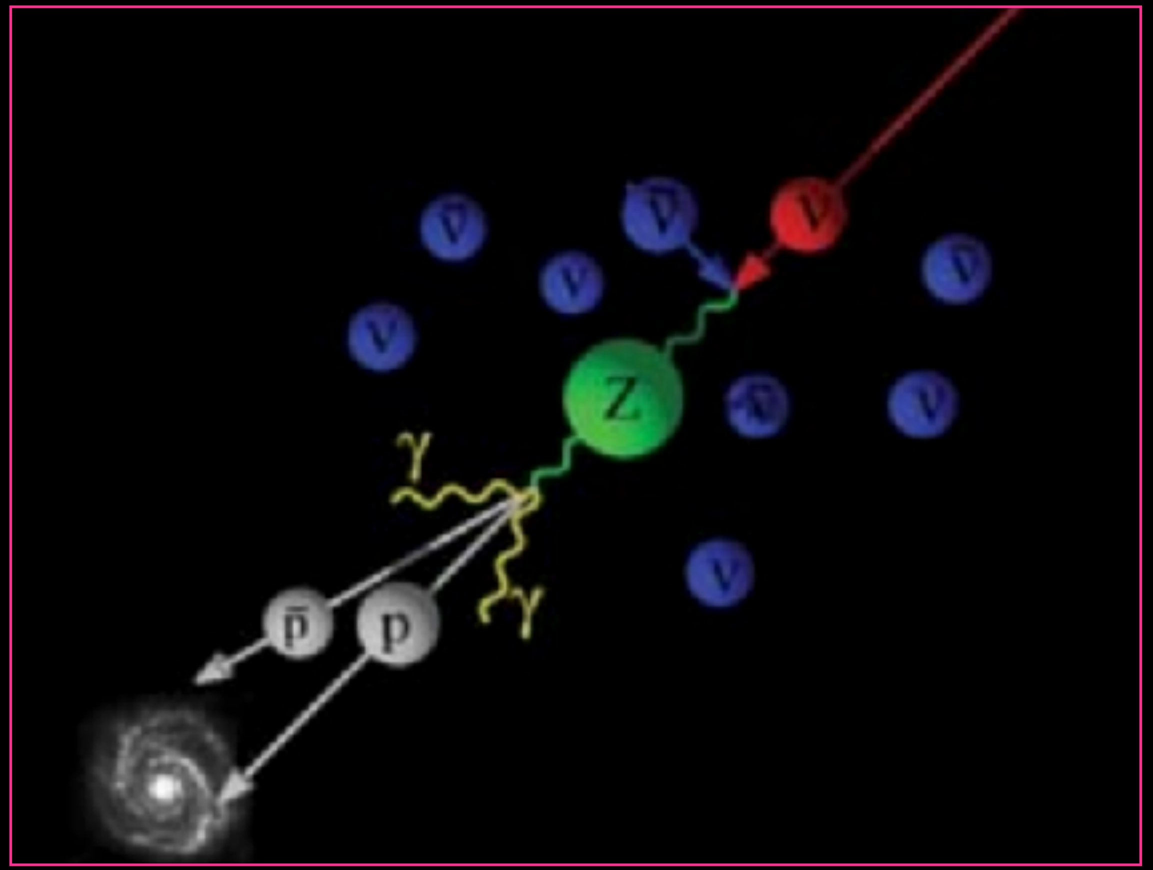
NON-SPHERICAL MASS DISTRIBUTION



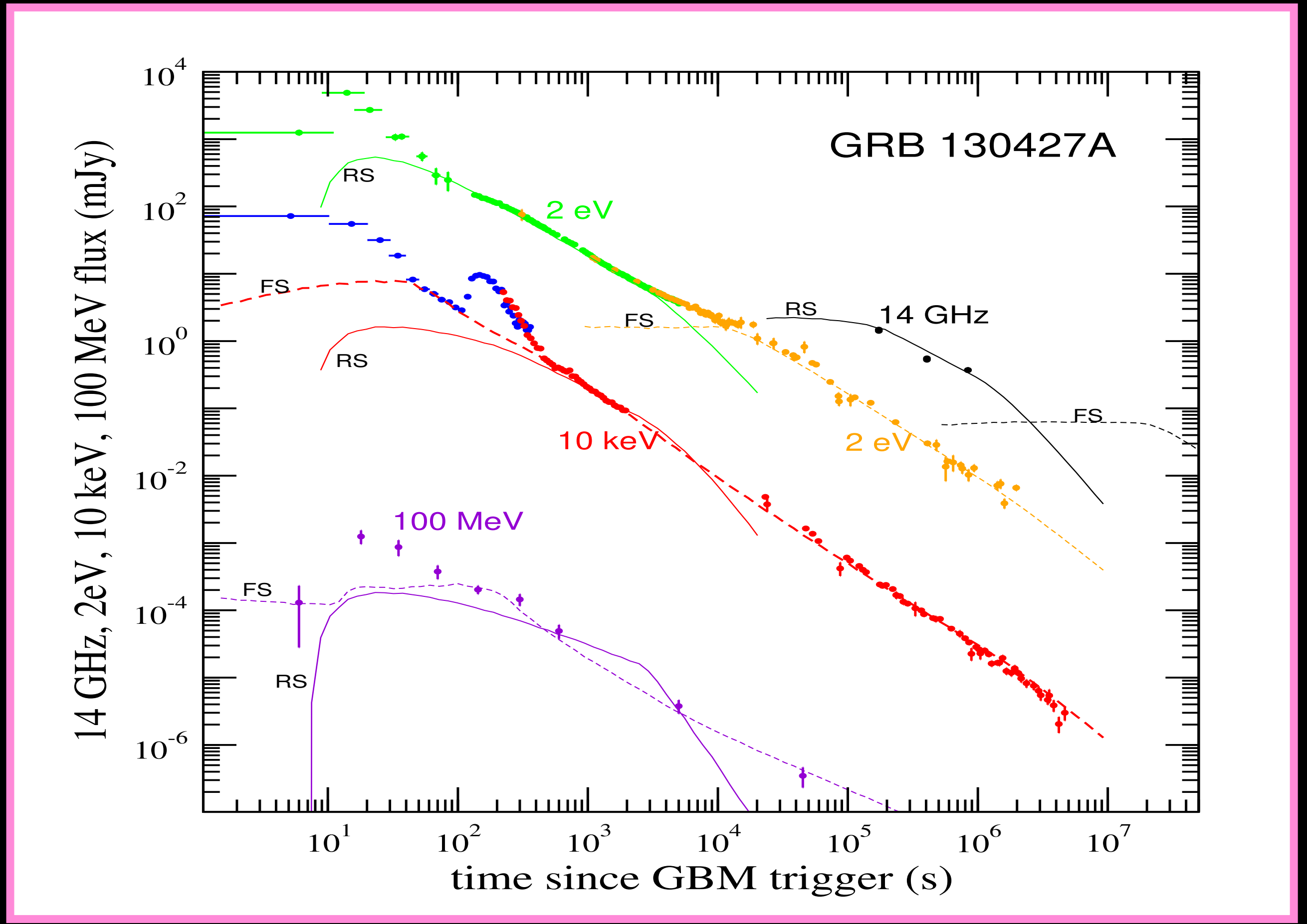


EMISSION POWERED BY RADIOACTIVE DECAY.

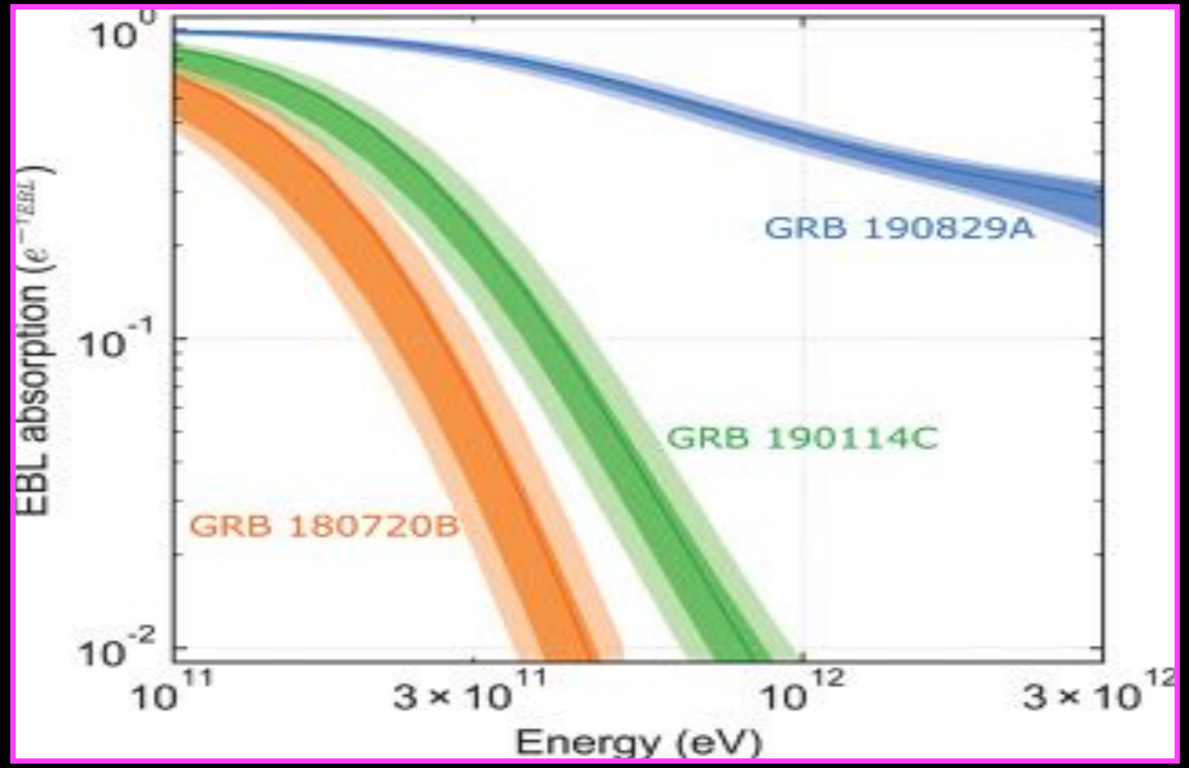
NEUTRINOS & COSMIC RAYS??



AFTERGLOW



UHE GAMMA-RAYS

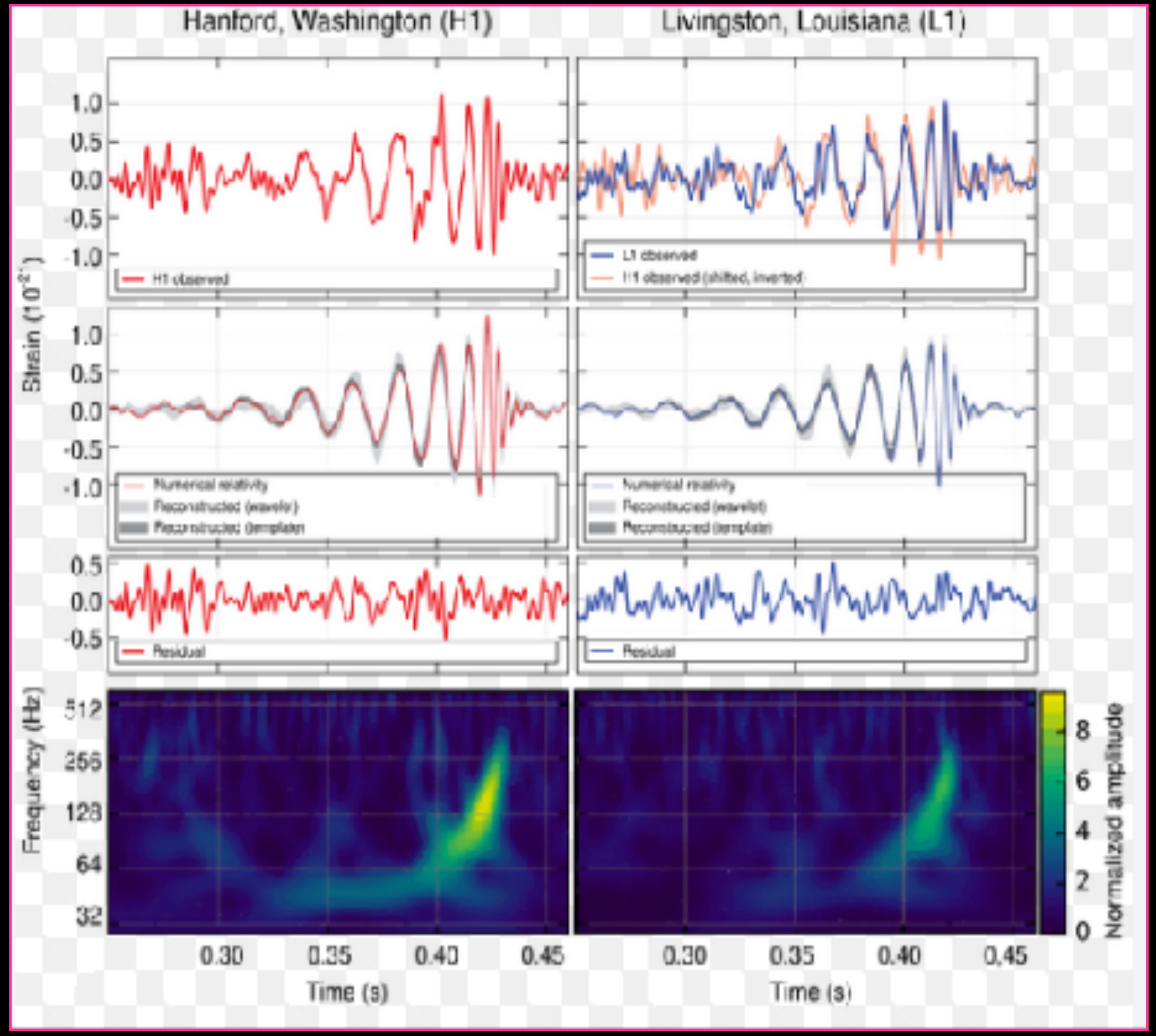


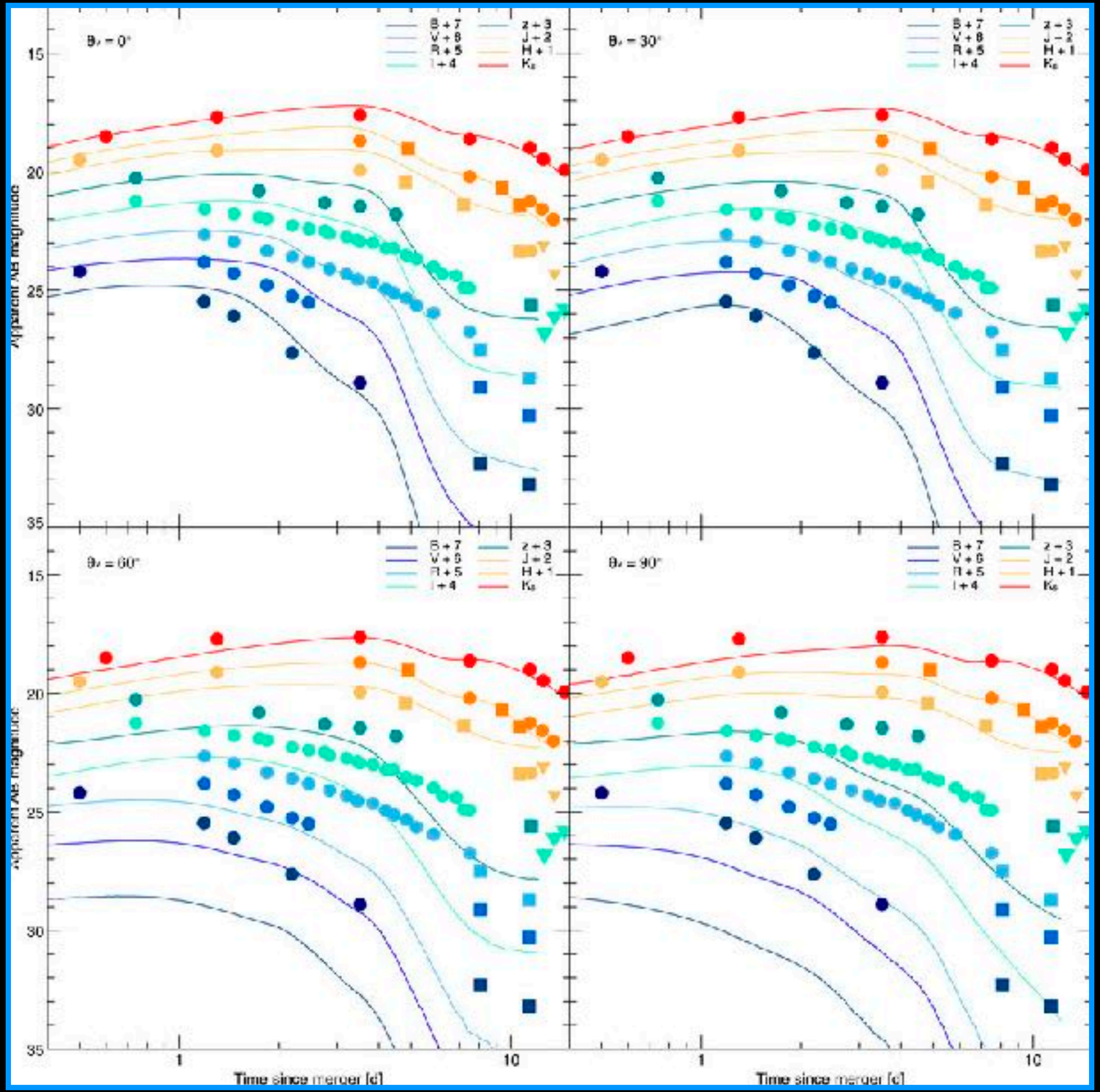
Kilonovae

Data sources:
K. Lodders, ApJ 591, 1220 (2003)
M. Arnould et al., Phys. Rep. 450, 97 (2007)

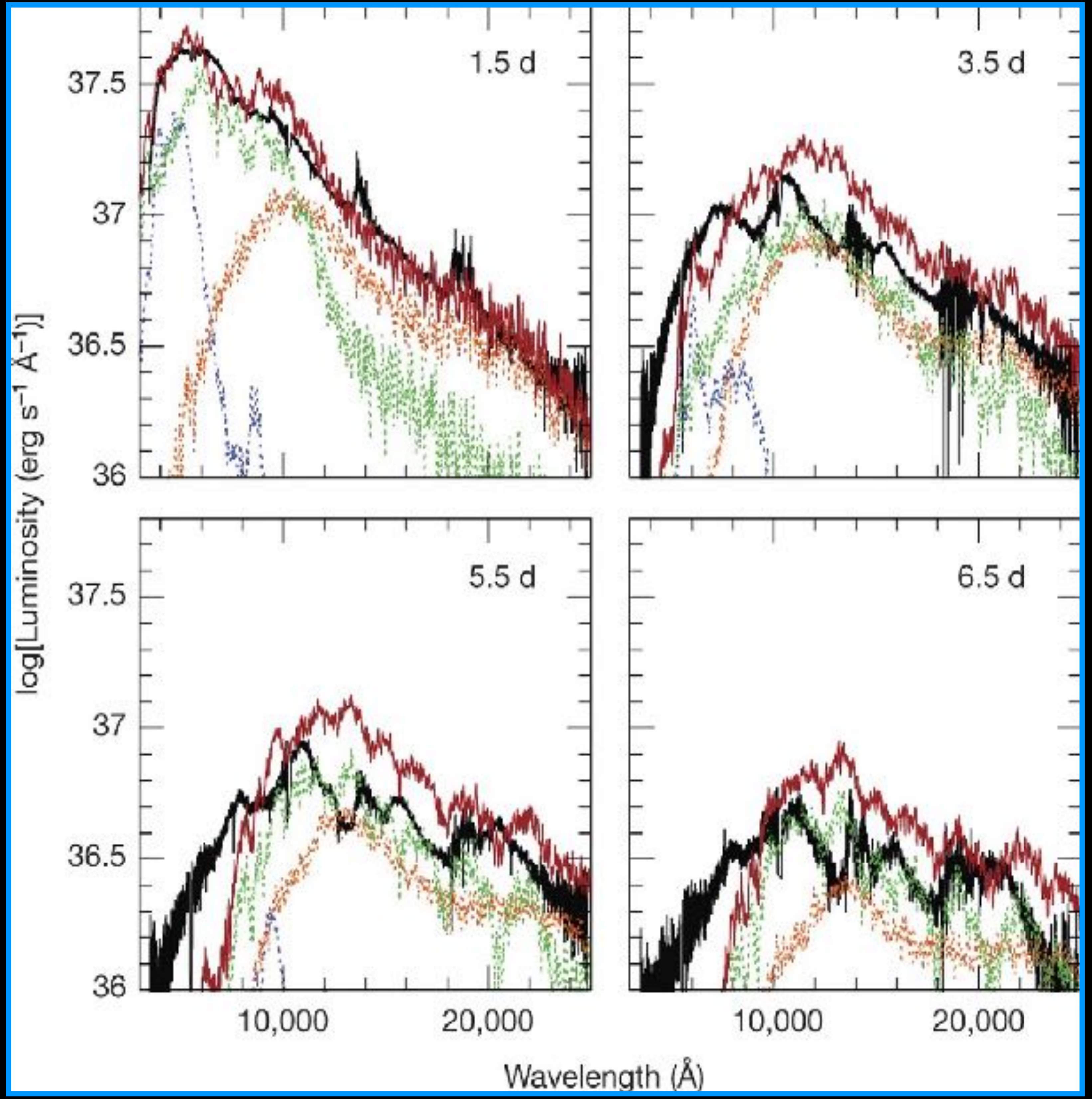
Courtesy of Jonas Lippuner

Kilonovae associated with short GRBs – GRB170817
Double neutron star merger origin



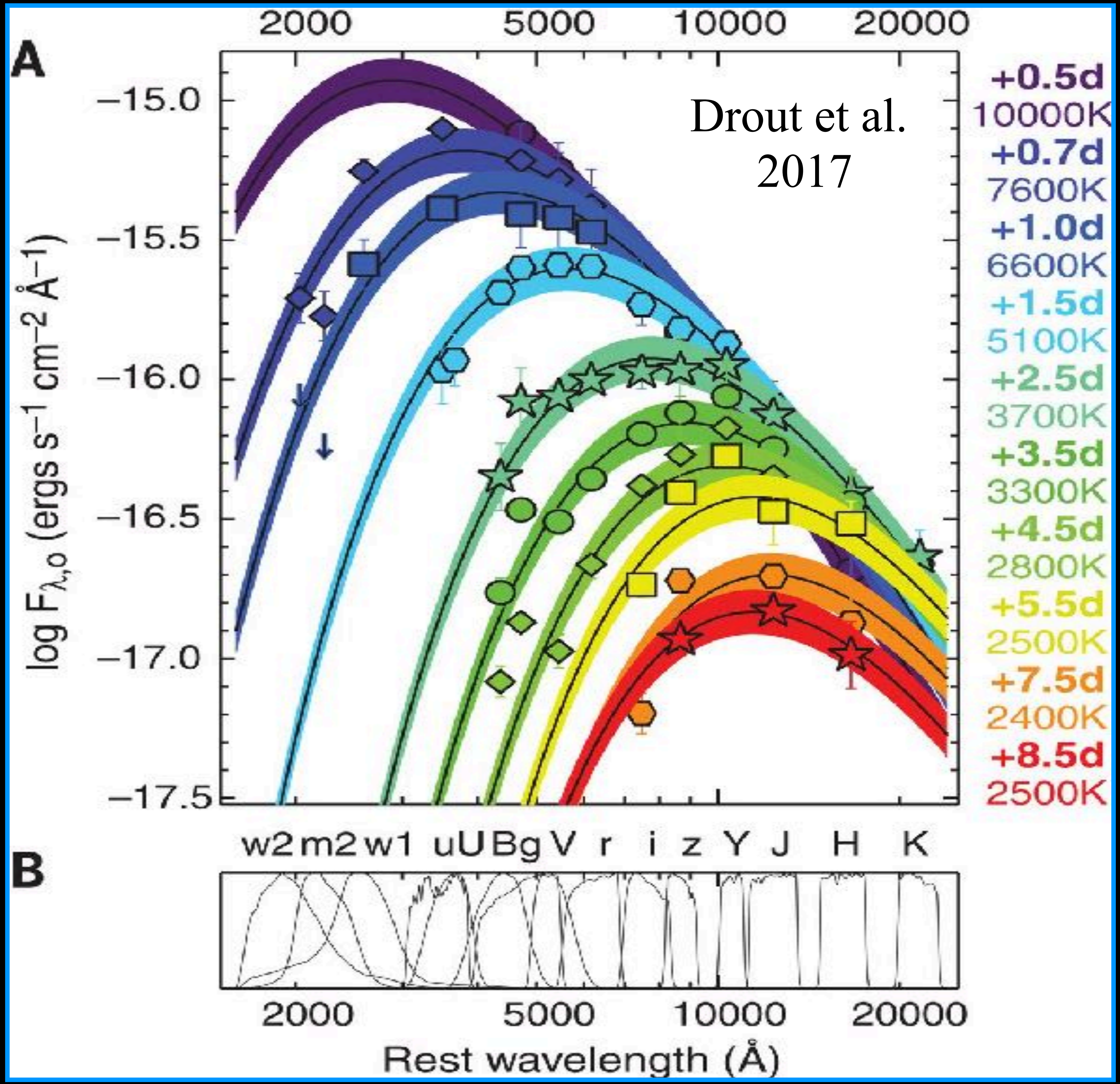


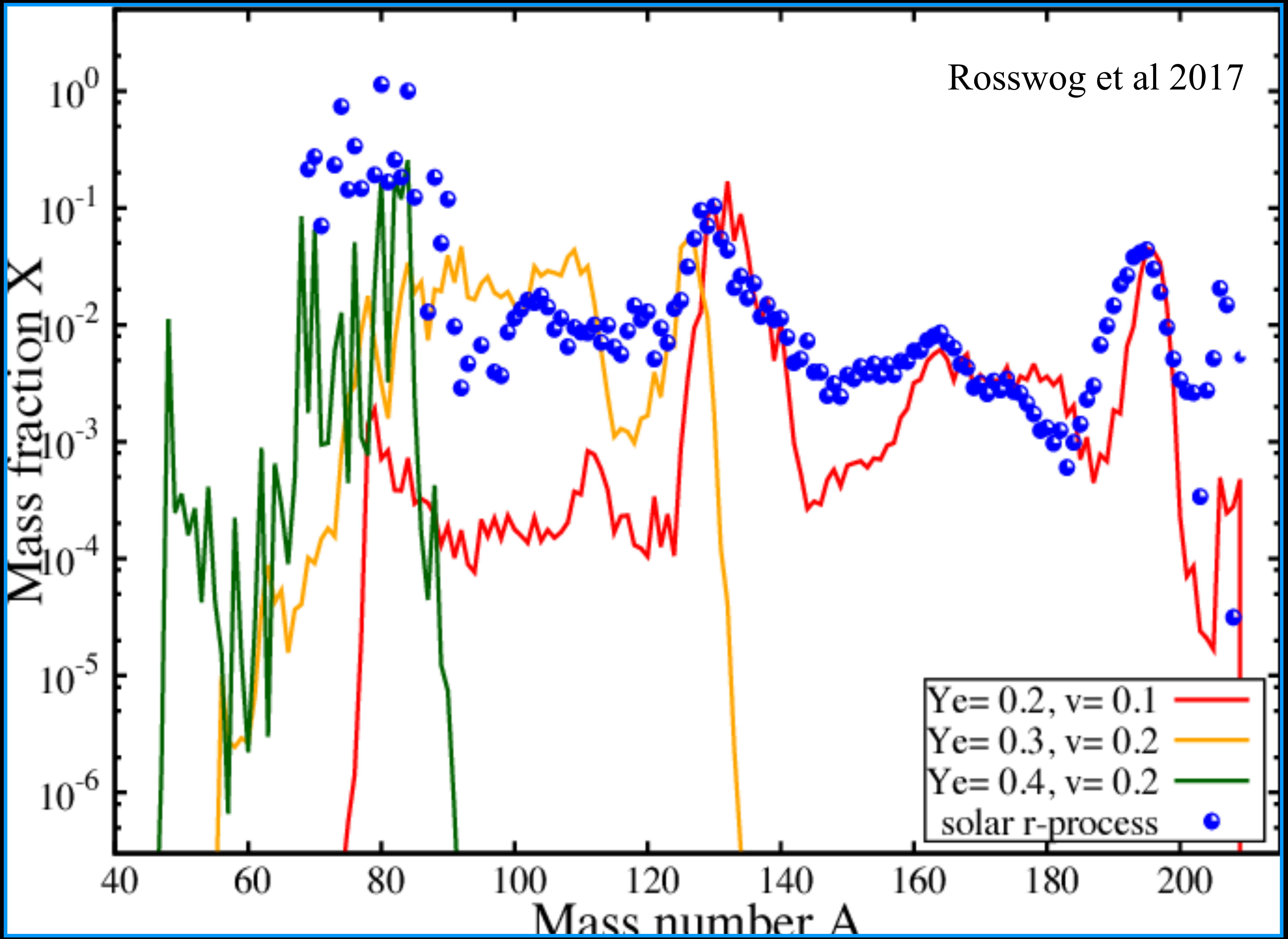
Kilonova light curves (models at different viewing angles)
Troja et al 2017



Kilonova spectra at different times (data in black)
Pian et al 2017

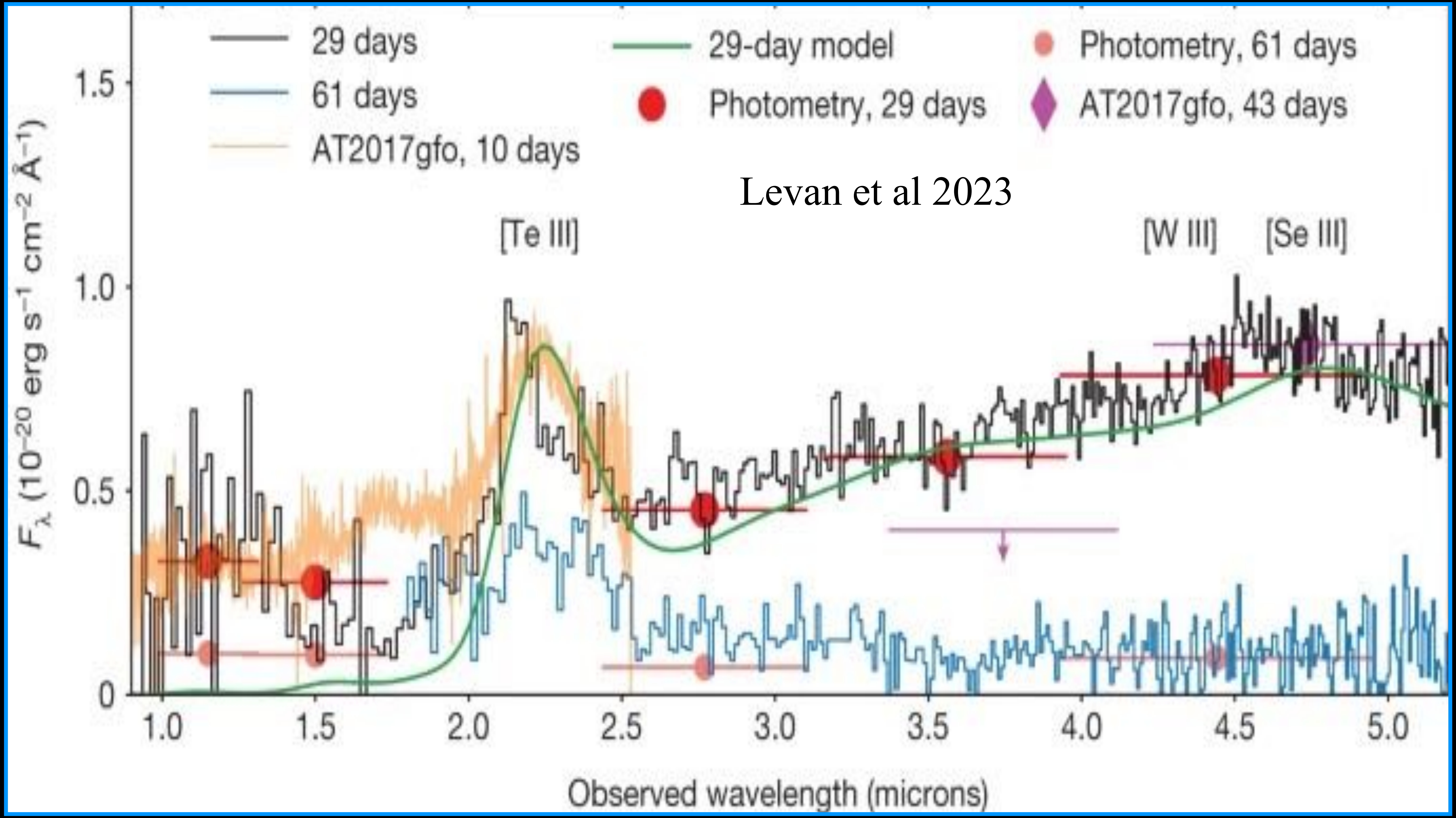
Kilonovae and r-process in double neutron star mergers

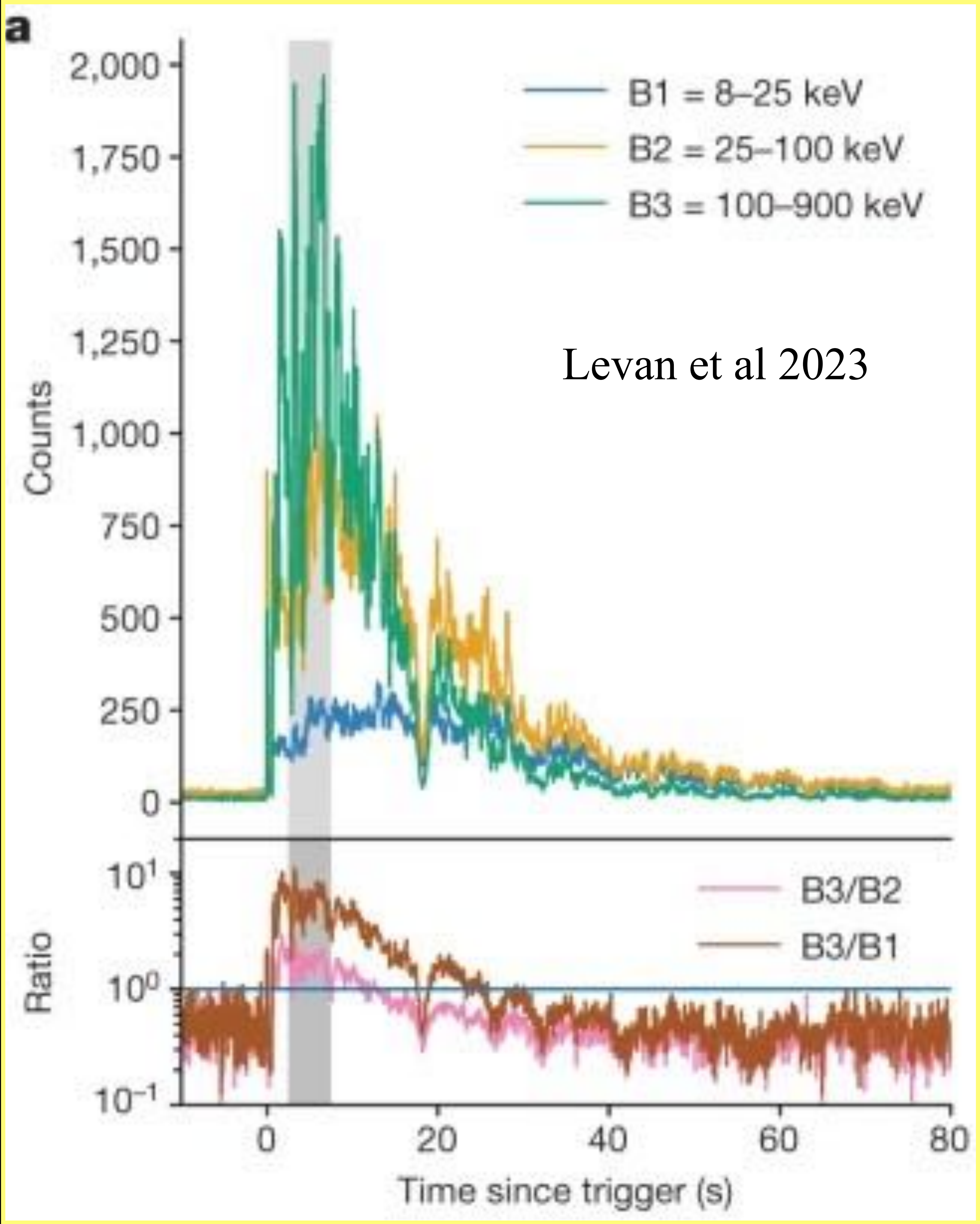




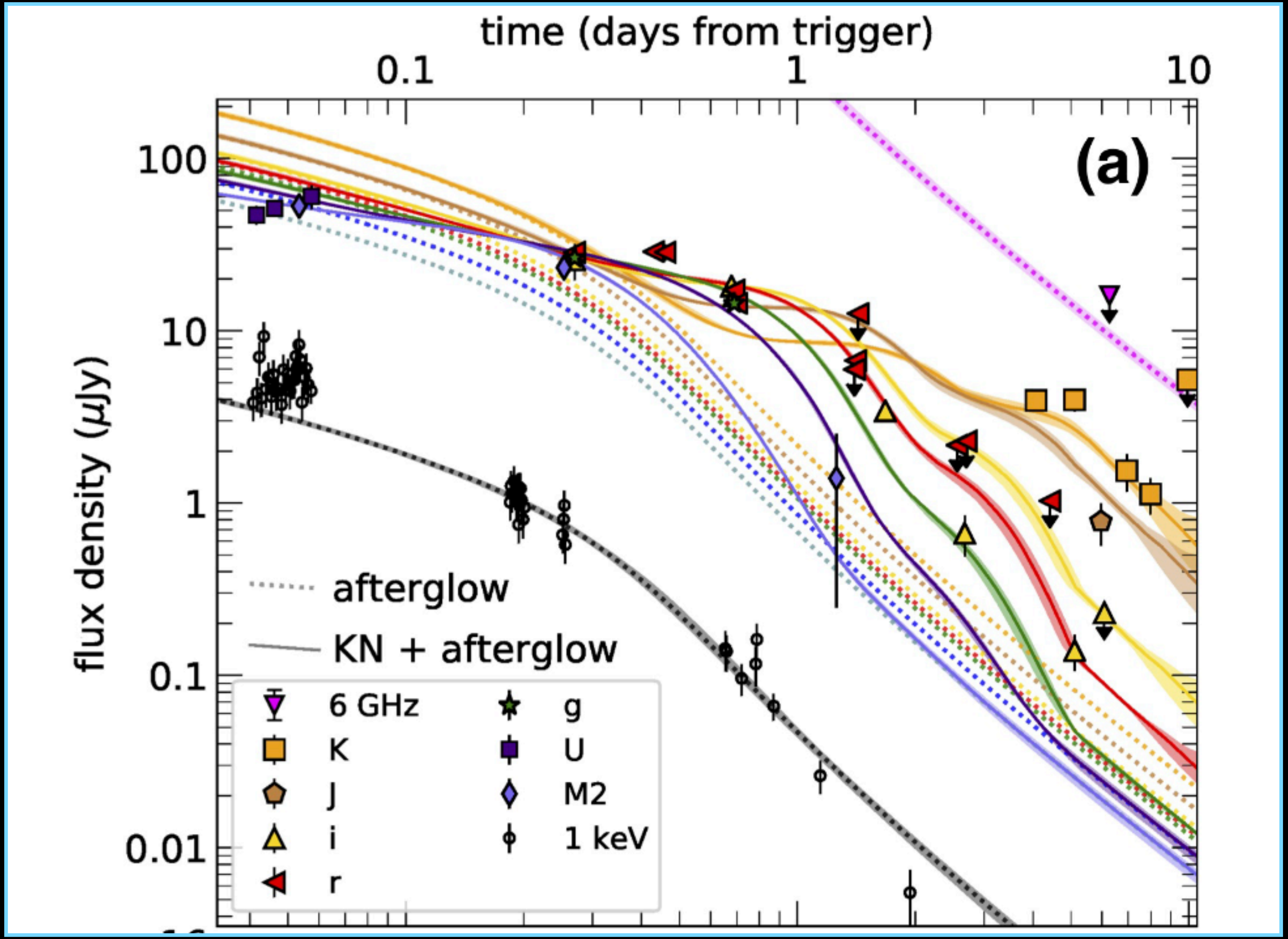
Kilonovae associated with long GRBs – GRB230307A

Clear emission feature seen at ~2.14 microns at both 29 and 61 days, consistent with TeIII. Redder features compatible with lines from Se III and W III

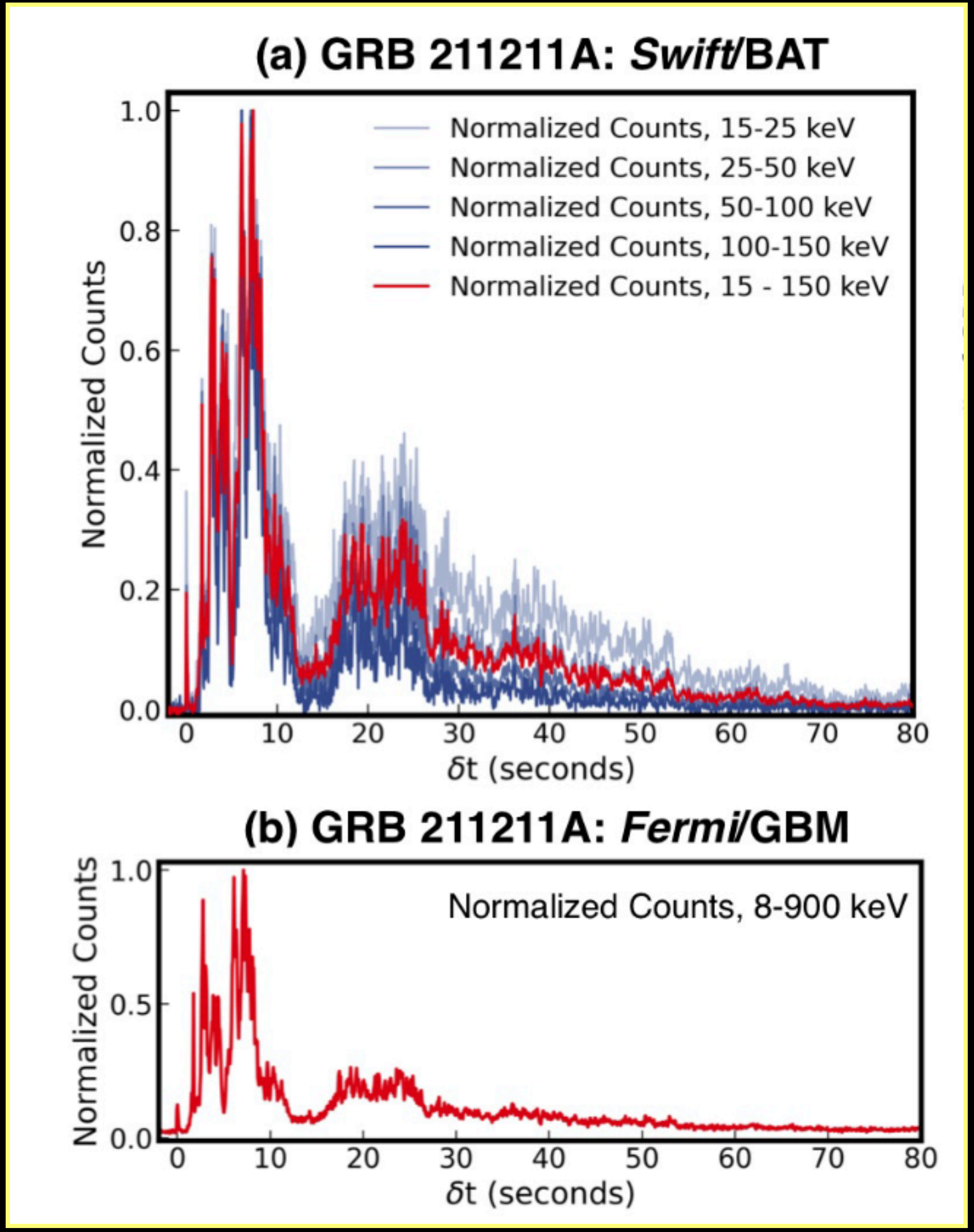




Kilonovae associated with long GRBs – GRB211211A



Rastinejad et al 2022

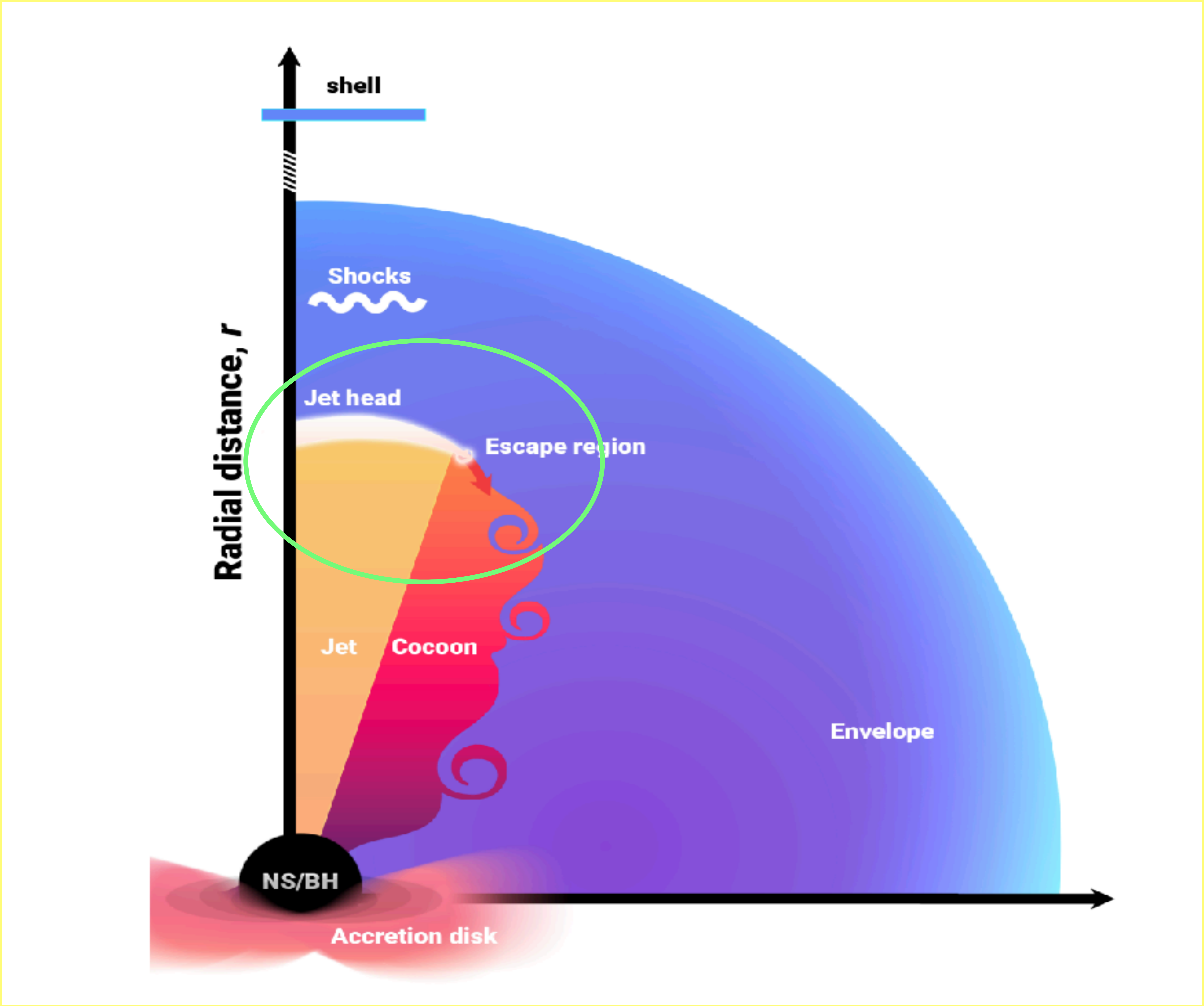


Double neutron star mergers as r-process sites:

- not easy to make a long GRB (GRB230327, GRB211211A)
- struggle to explain the abundances of very metal poor stars in the Milky Way (e.g. C. Kobayashi et al 2023)

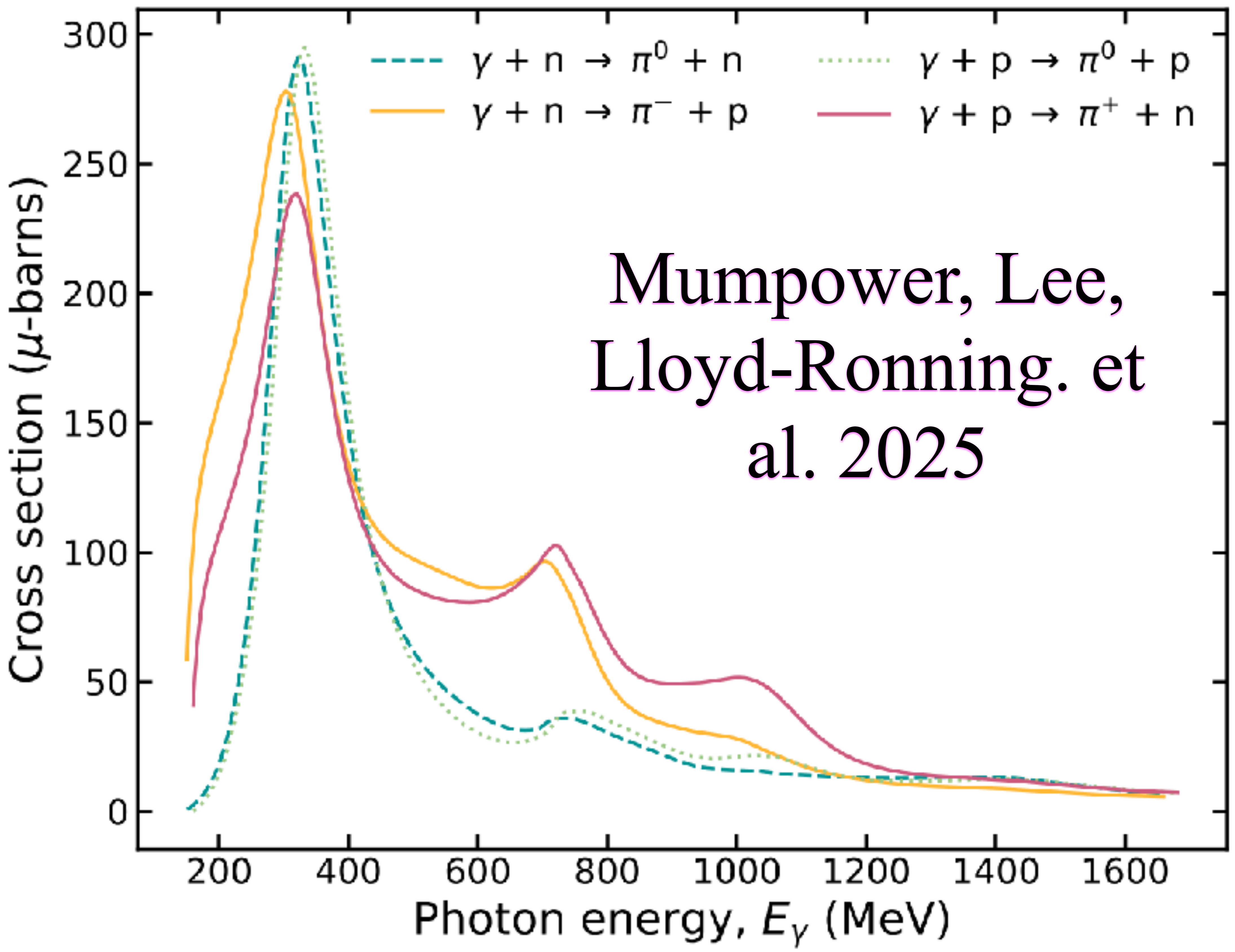
R-process in collapsar jets!

Neutrons from hadronic photo production in collapsar jets



Mumpower, Lee, L-R. et al. 2025

ANL-Osaka Photohadronic Cross Section



$$r_n = n_p \int \Phi(E_\gamma)\sigma_{\gamma p}(E_\gamma)dE_\gamma$$

Model jet-cocoon-envelope region

$$T(t) = T_o(\rho(t)/\rho_o)^{\gamma-1}$$

$$\rho_{env}(r) = \rho_o(r/R_g)^{-\delta}(1 - r/R_*)^3$$

$$\rho_{head} = \epsilon\rho_{env}$$

$$Y_e = \frac{Y_p}{Y_n + Y_p} = \frac{1}{\epsilon(m_p/m_e) + 1}$$

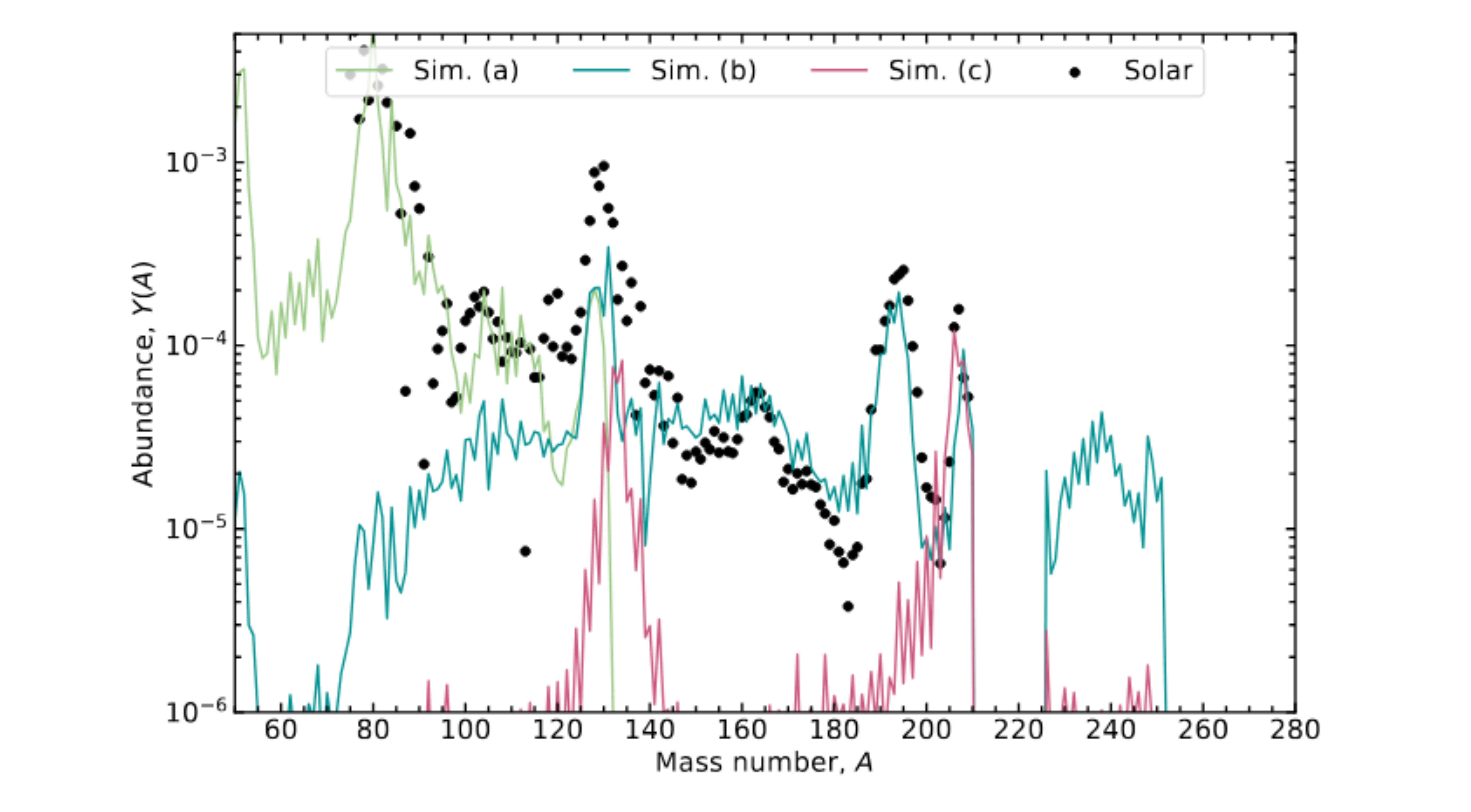
$$\rho(t) = \rho_o(1 + t/\tau_1 + (t/\tau_2)^{\xi})^{-1}$$

R–PROCESS AT JET HEAD IN A COLLAPSAR!

Sim A: Light r-process

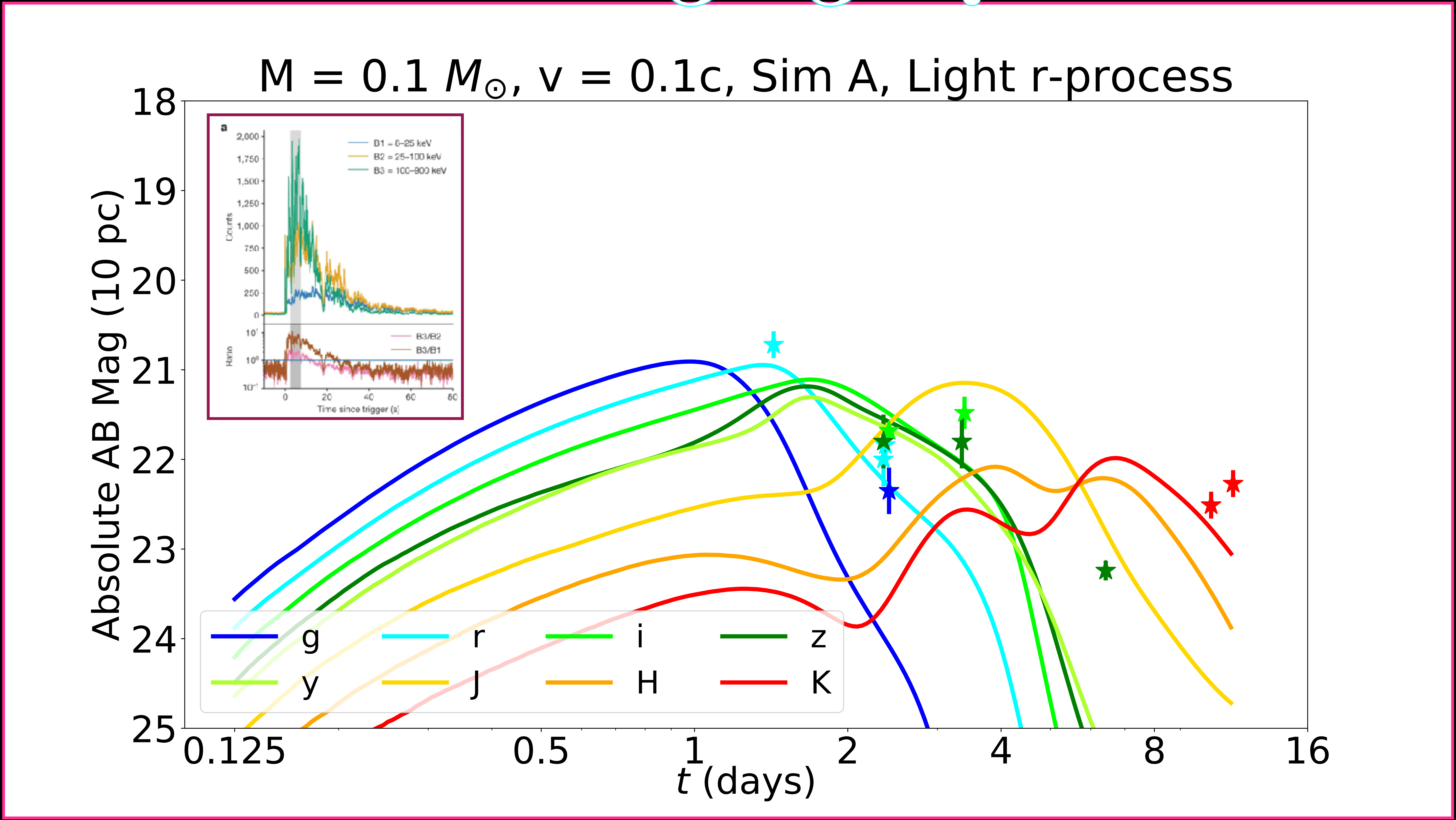
Sim B: Robust r-process

Sim C: i-process



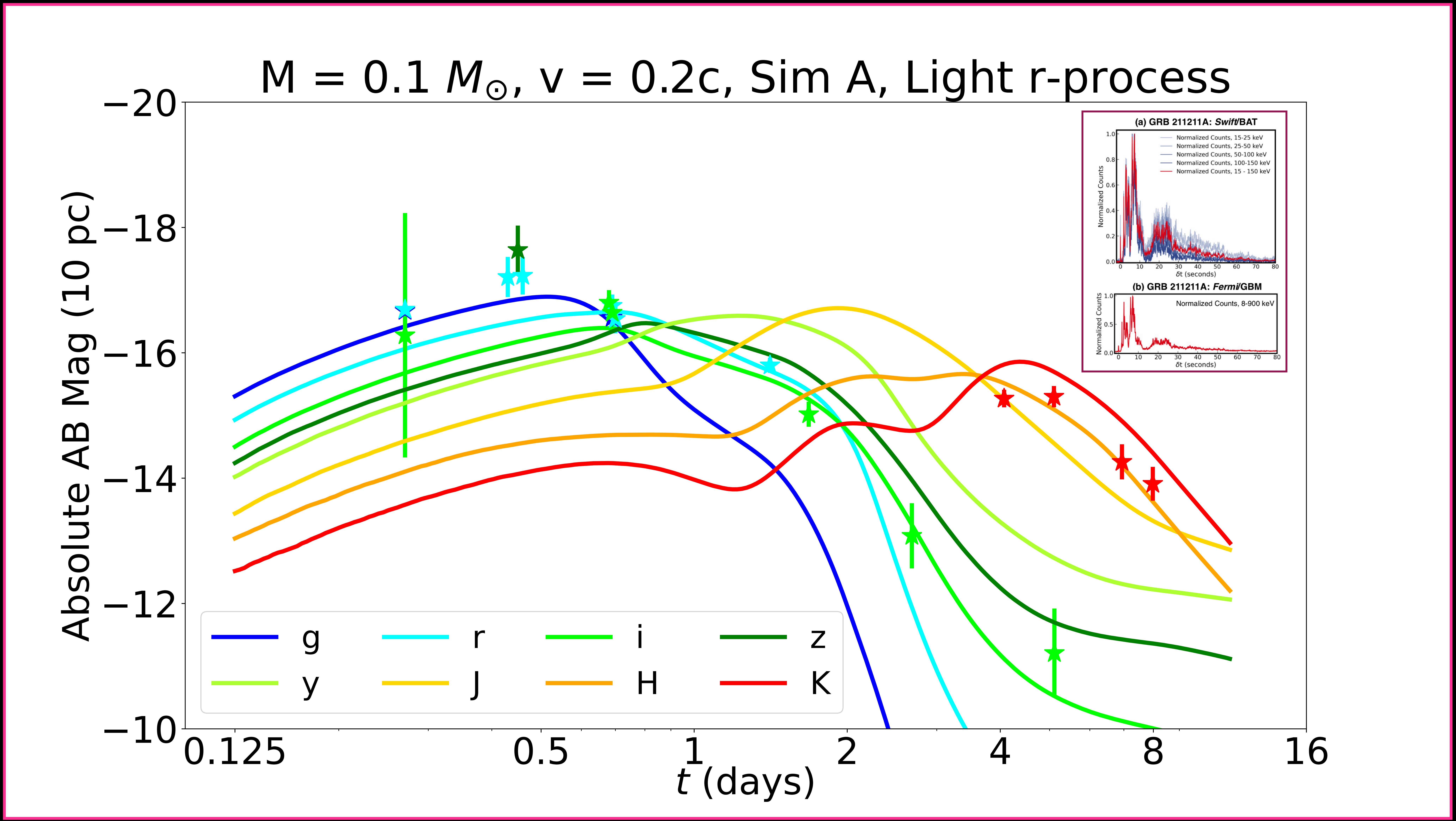
Mumpower, Lee, L-R. et al. 2025

GRB 230307A



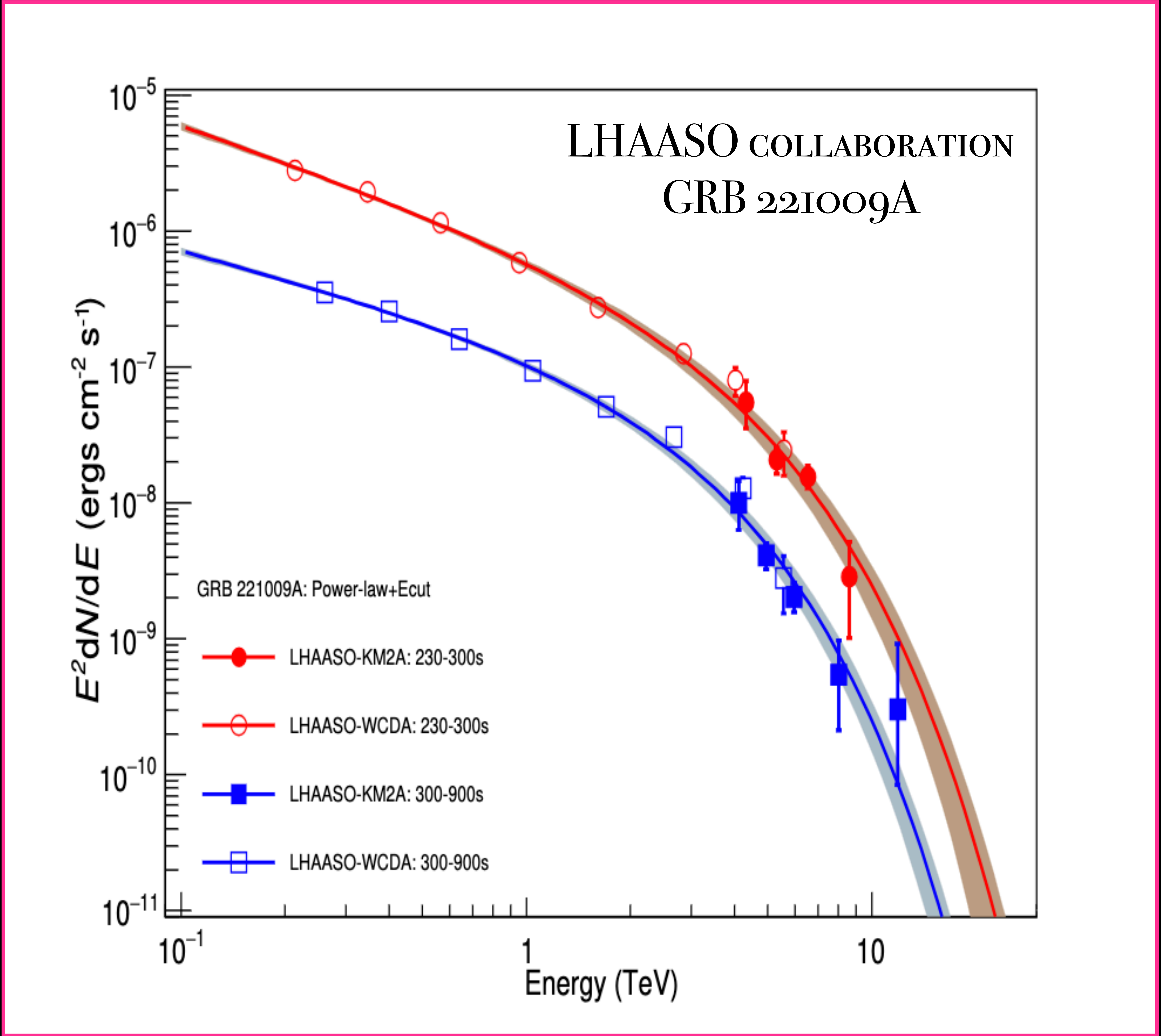
Courtesy Marko Ristic, Oleg Korobkin

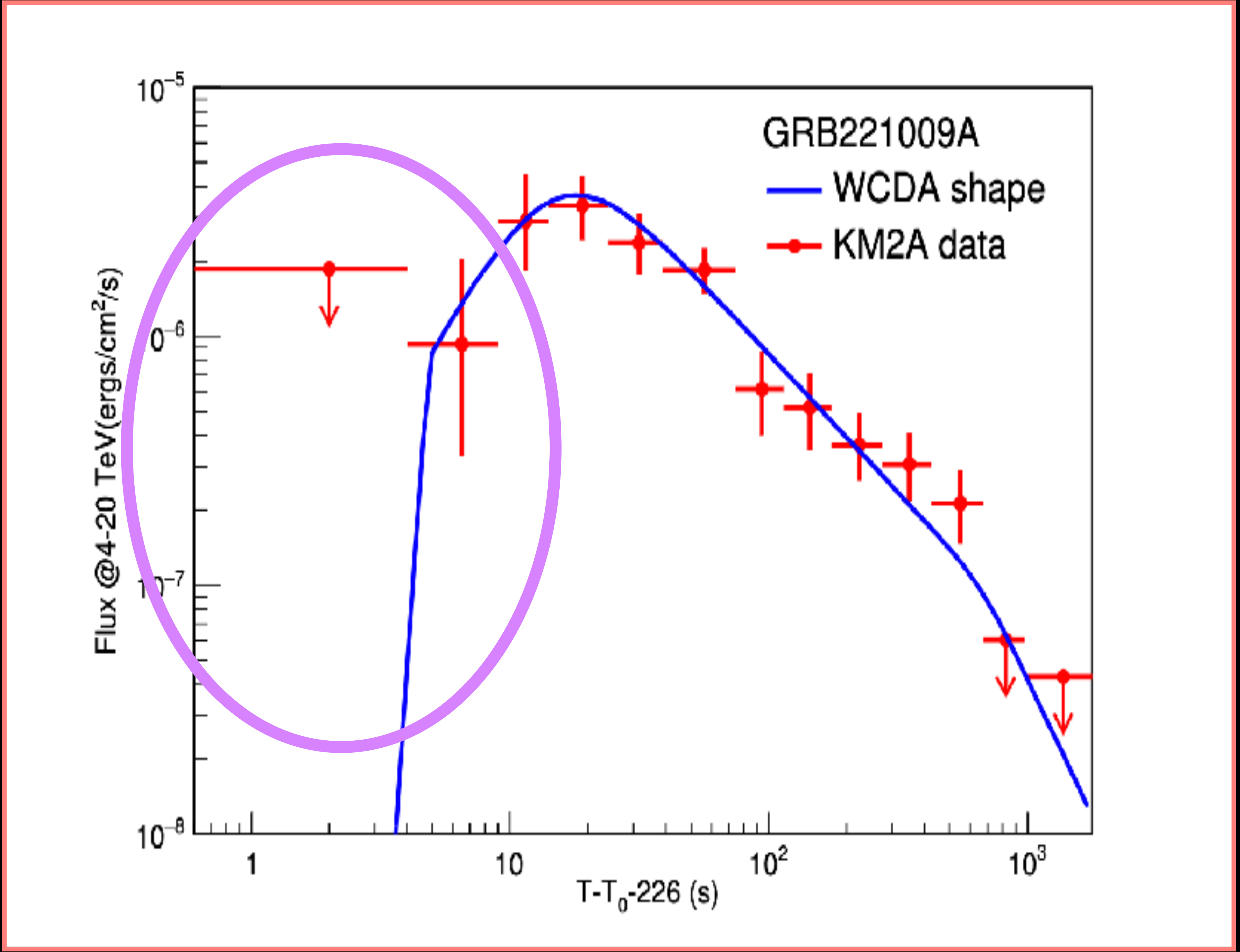
GRB 211211A



Courtesy Marko Ristic, Oleg Korobkin

Ultra high energy gamma-rays in GRBs

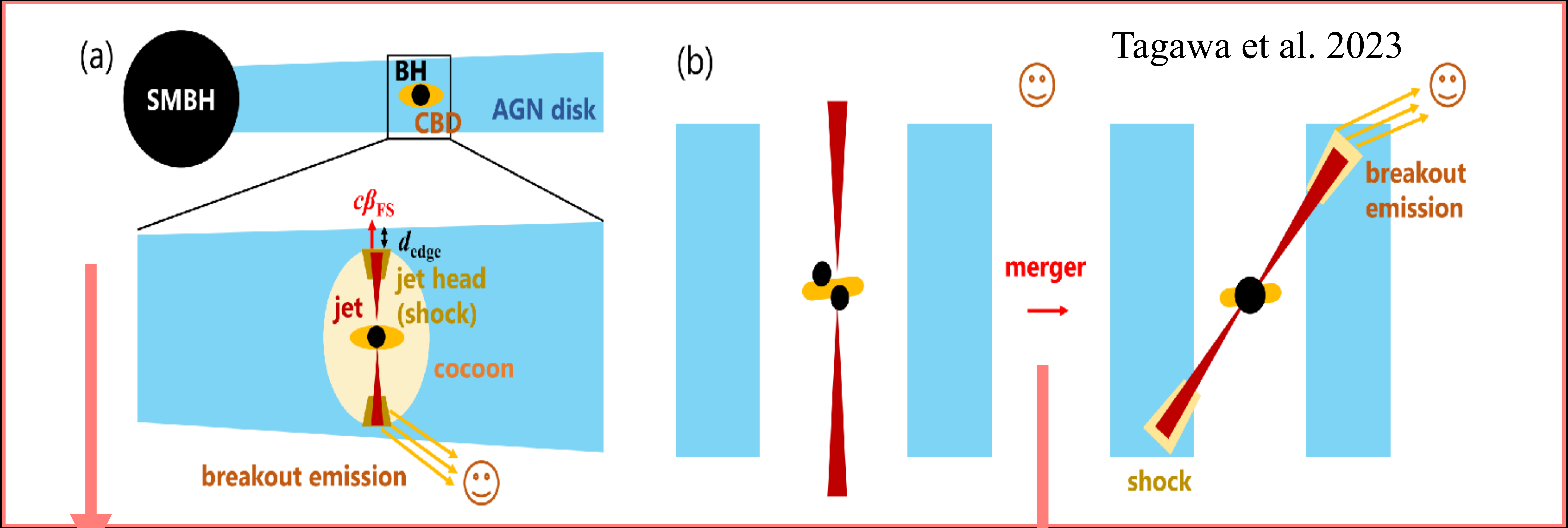




What? Where? How?

Time of onset is key

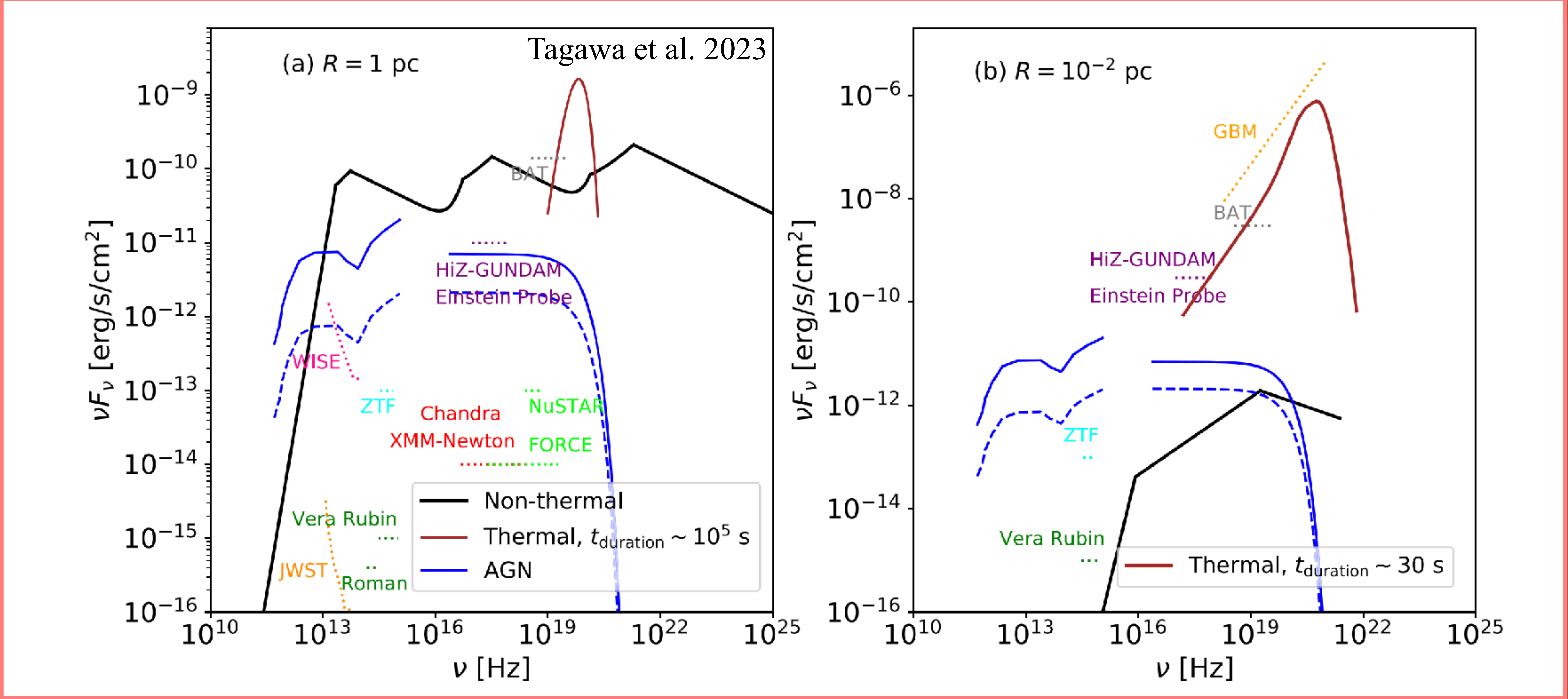
Binary Black Hole mergers in AGN Disks



Breakout emission from a solitary black hole embedded in an AGN disk - produced episodically after replenishment of gas to the black hole (see Tagawa et al. 2022)

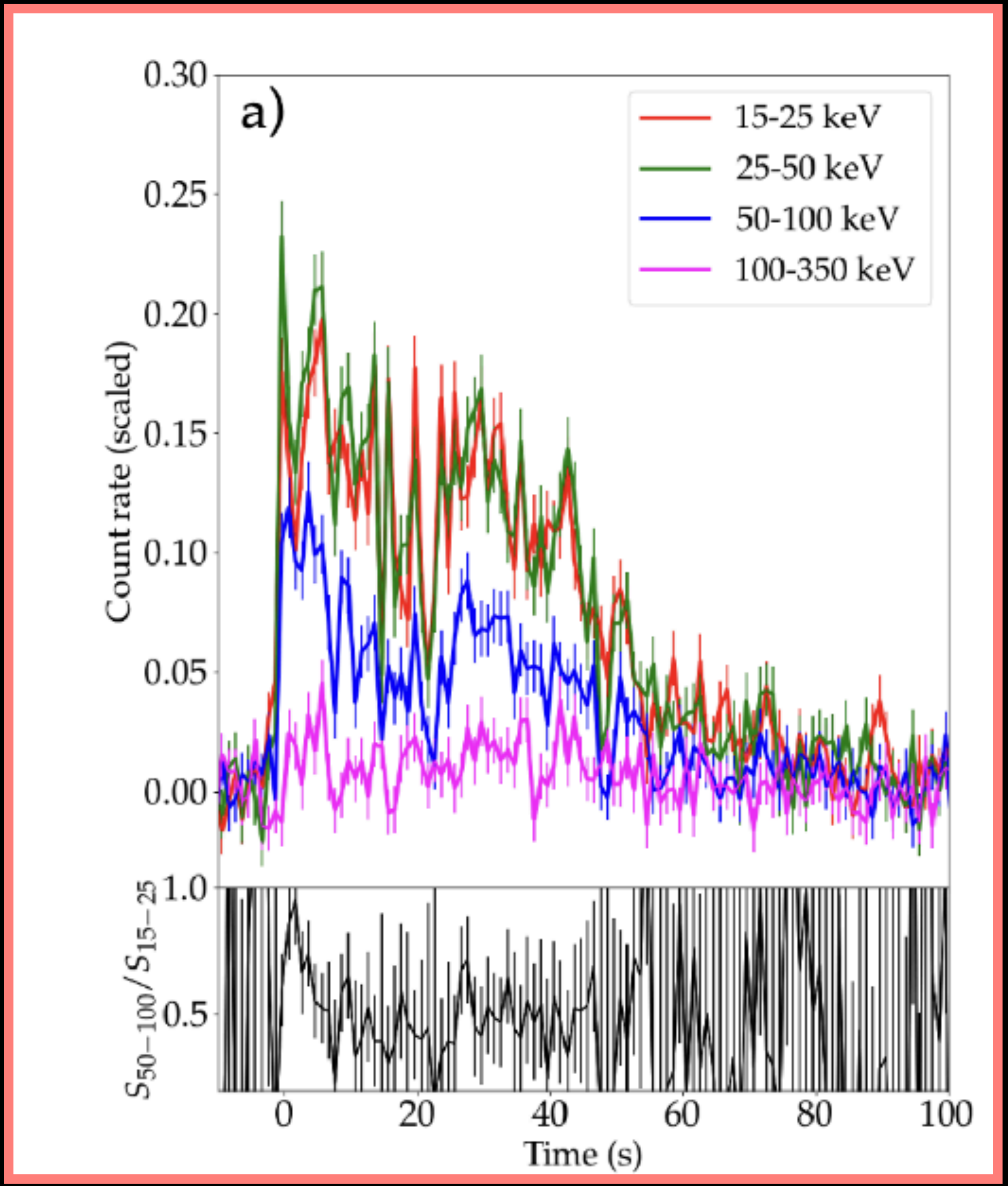
Breakout emission from a merger remnant spin reoriented after merger, and the jet again collides with unchecked AGN gas, producing emission after the merger.

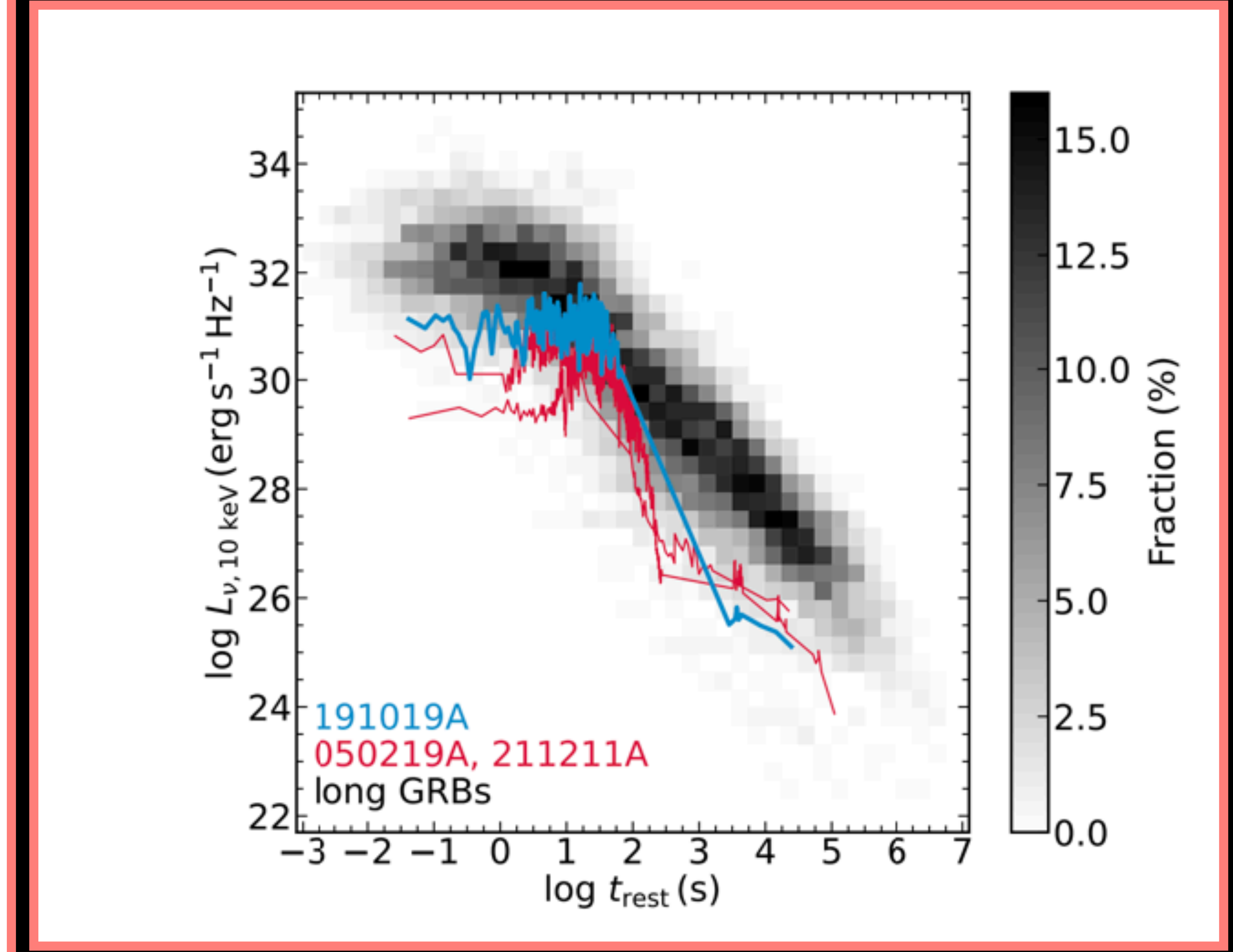
Spectra of BBH mergers in AGN disks

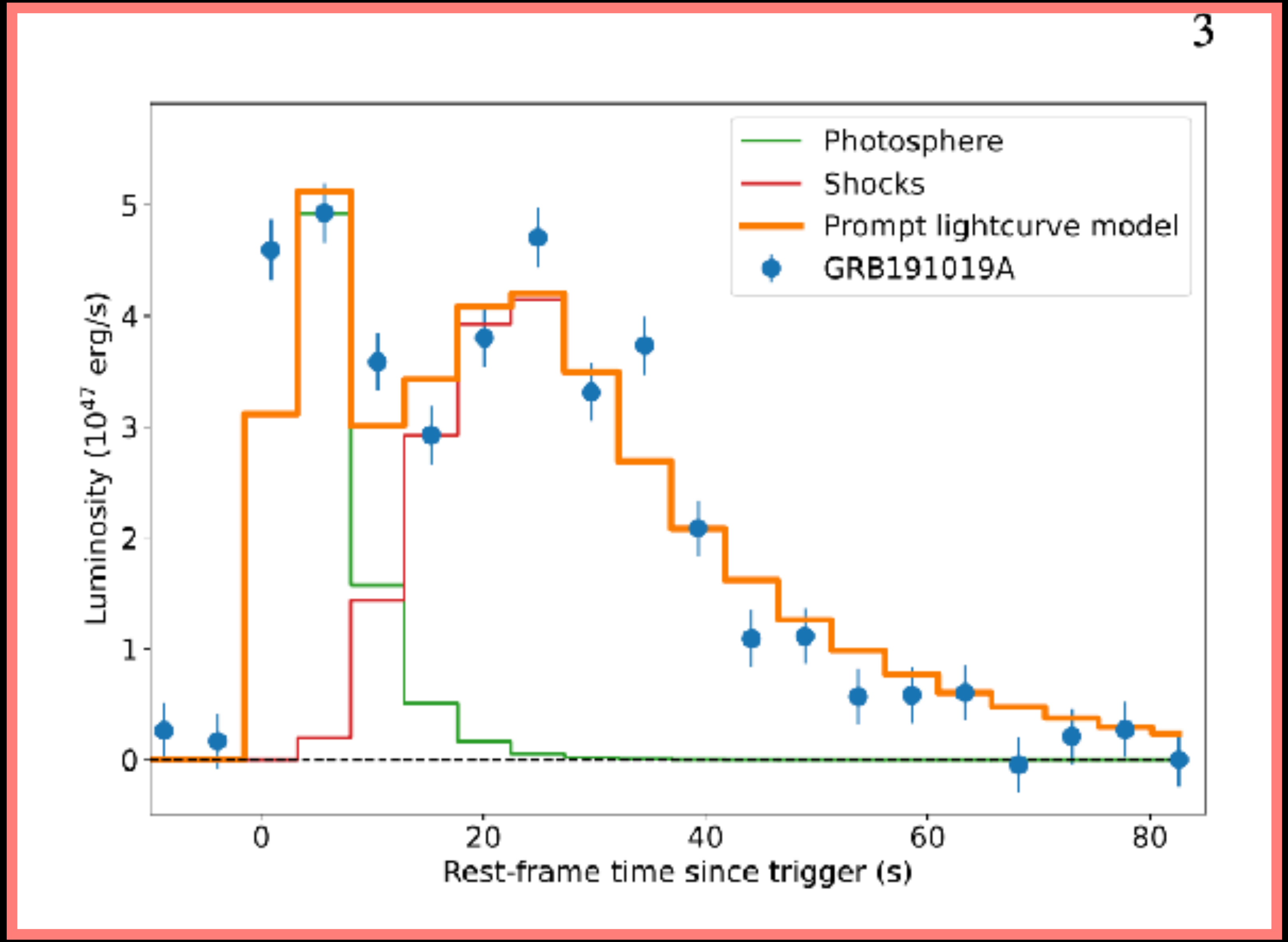


Meanwhile, timescale and lightcurves depends on many things…

BBH mergers in AGN disks: GRB 19019A



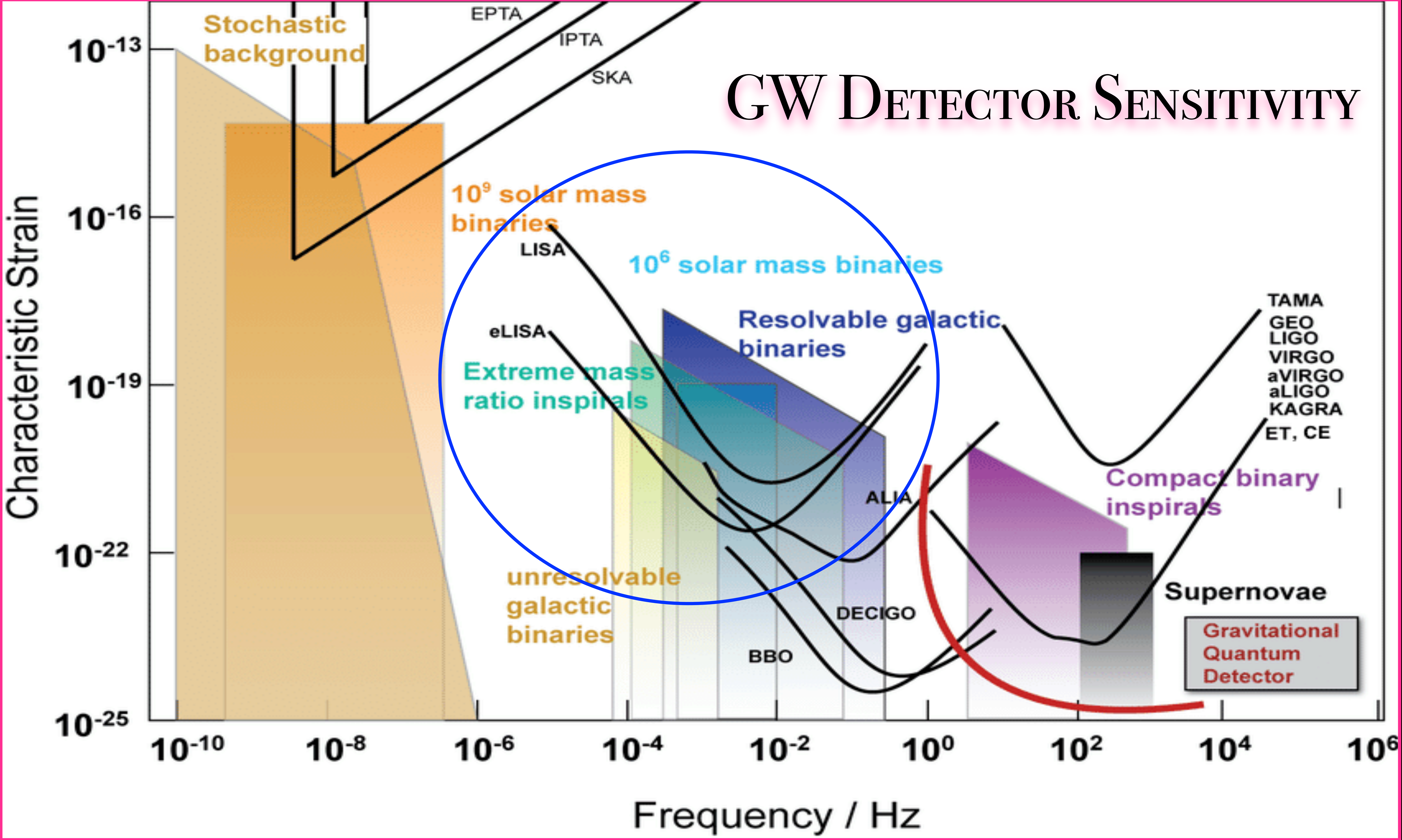




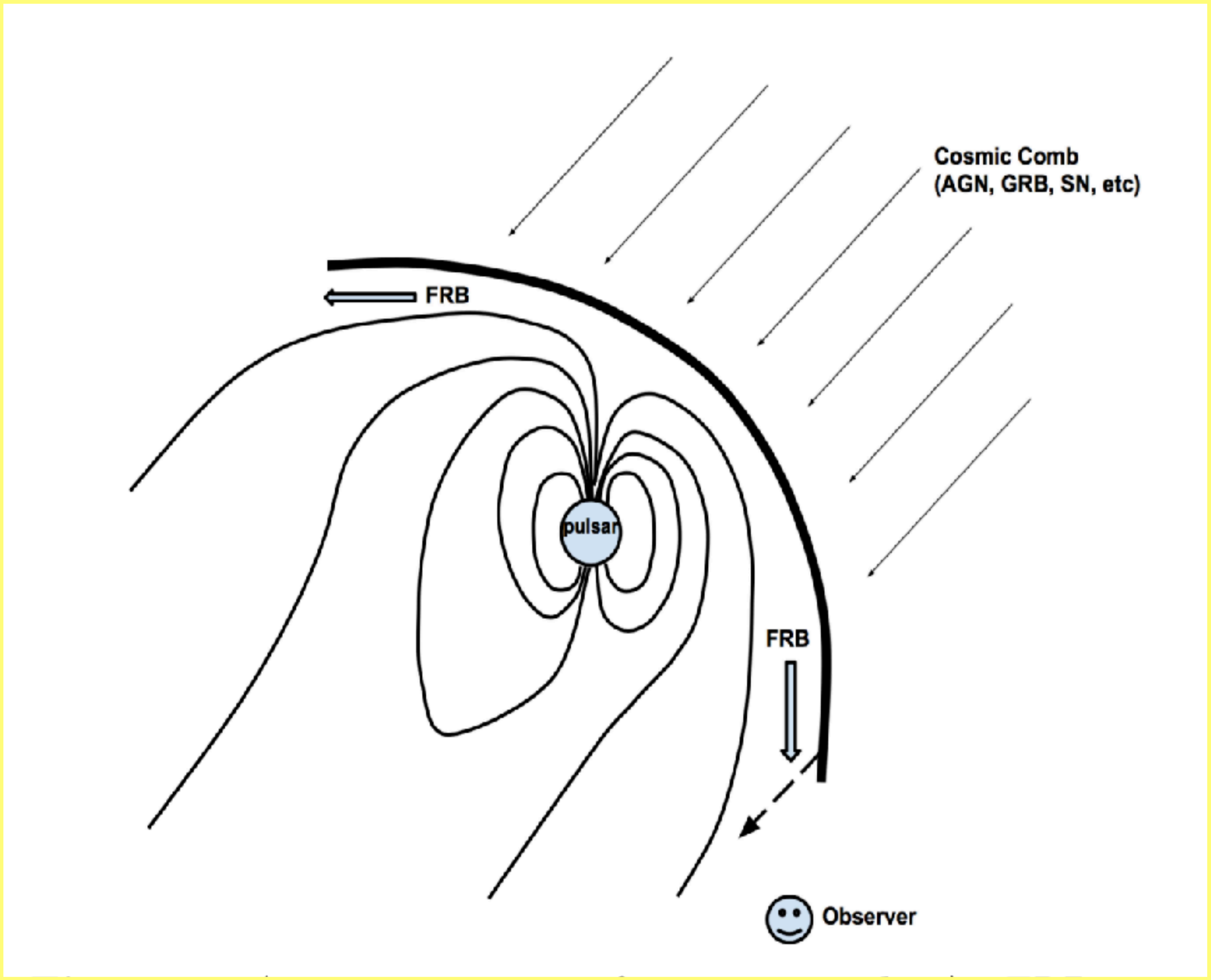
Long GRB (T90 ~ 65s) located < 100pc to nucleus of old (>1Gyr) galaxy, no star formation, z=0.248. GRB luminosity more consistent with sGRB. (Levan et al. 2023)

Fit well by external shock/ reverse shock scenario: BBH merger in very dense medium e.g. AGN disk. (Lazzati et al. 2023)

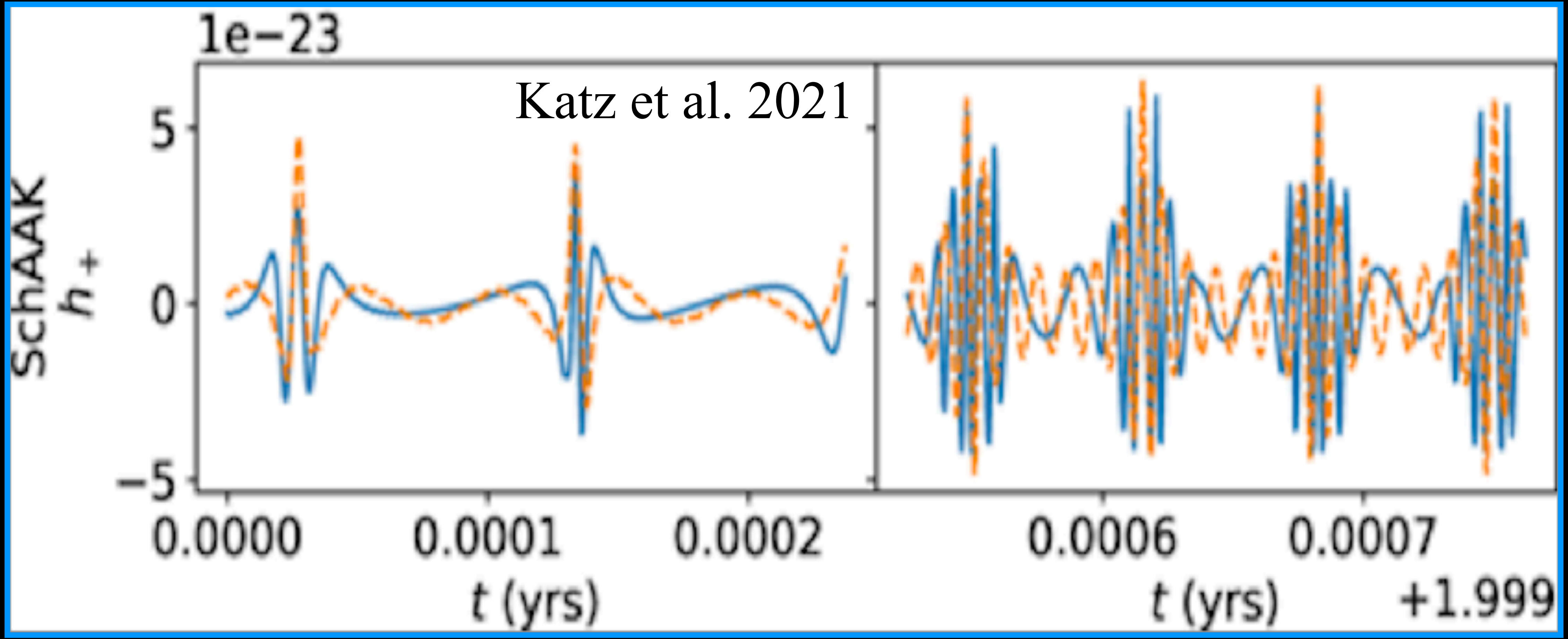
GW Detector Sensitivity

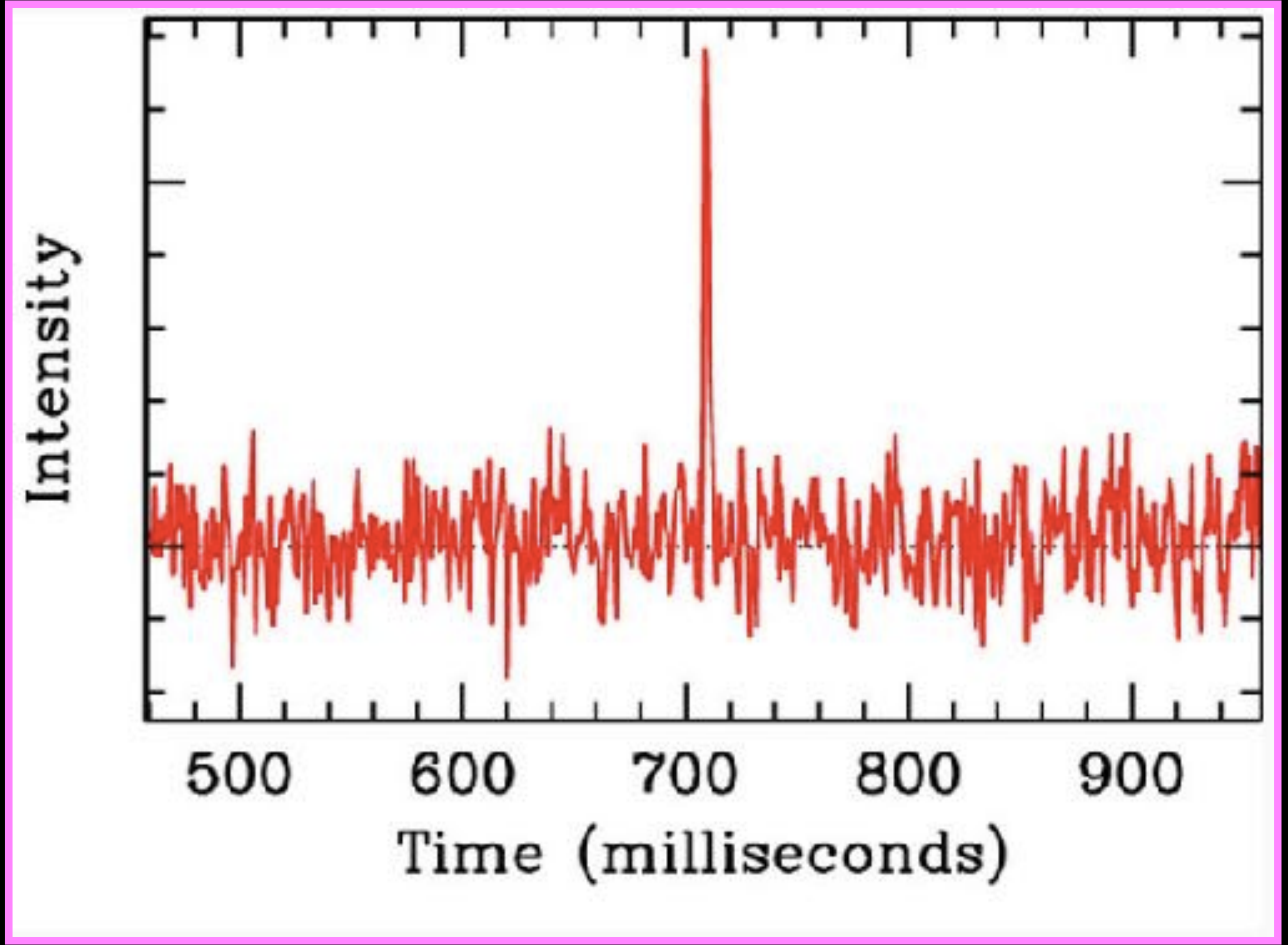


Extreme mass ratio inspirals and FRBs



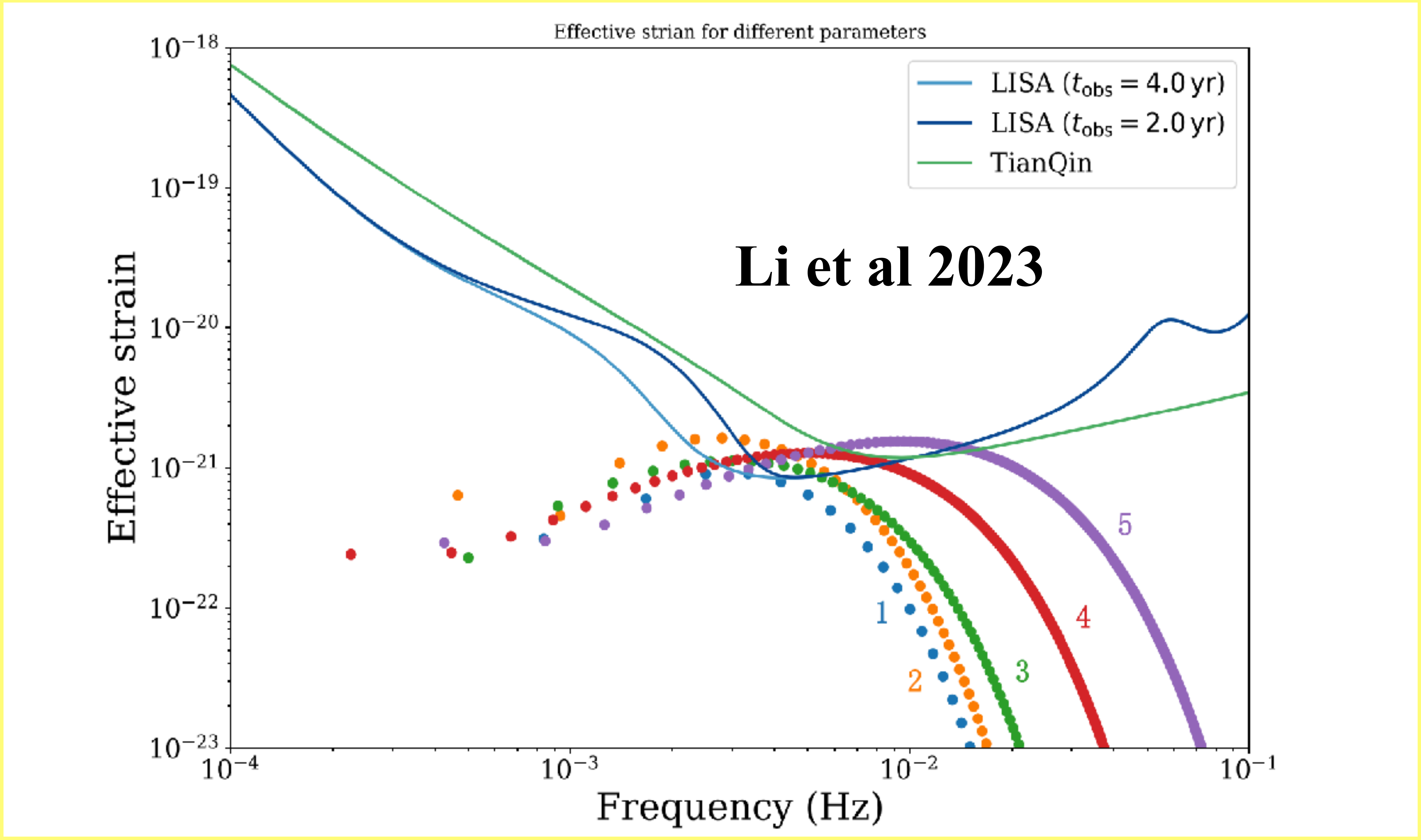
Cosmic Comb; Zhang 2017





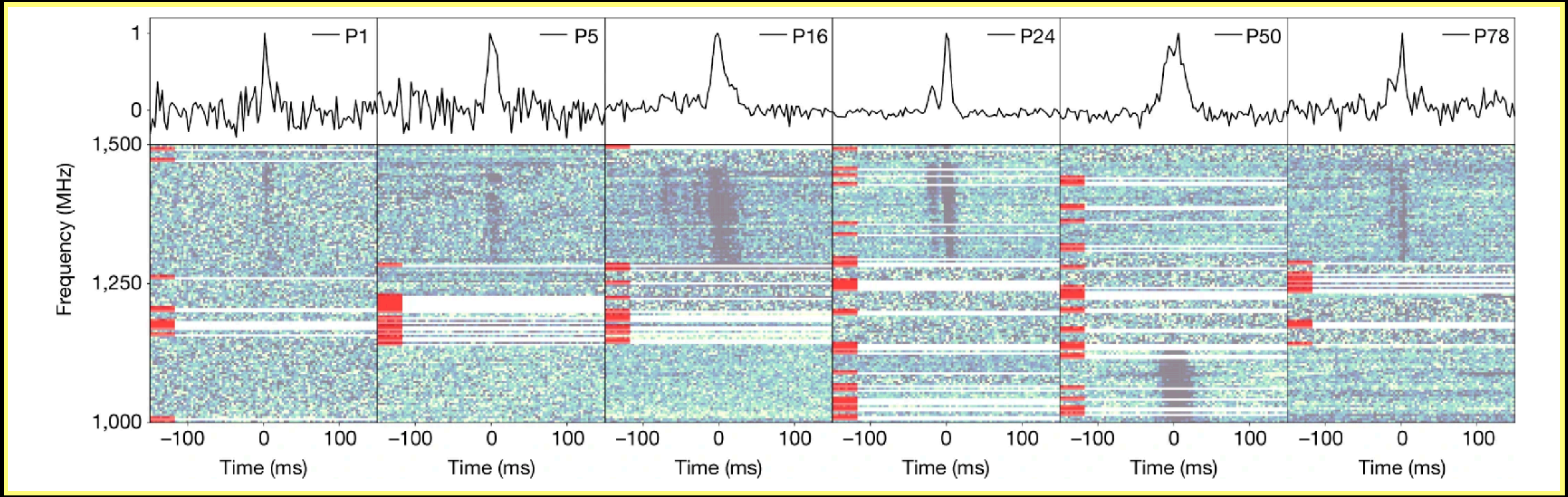
Ram pressure of stream > magnetic pressure of magnetosphere. Field modified, large energy release on short timescales — FRB!

EMRI-FRBs: Cosmic comb and GW signal



Case	M_{BH} (10^5 $M_\odot$)	f (10^{-6})	B_S (10^{14}G)	P_S (s)	B_r (mG)	a_{uplim} (10^{-7}pc)	e_0	RM_{lowlim} (rad m^{-2})	DM (pc cm^{-3})	z_{max}	t_{merge} (yr)
1	1	10	1	2	10	2.54	0.5	1.99×10^5	25	0.03	61
2	10	1	1	2	1	8.05	0.65	1.99×10^4	25	0.04	62
3	10	10	1	2	3.2	25.4	0.9	2.01×10^5	79	0.01	6190
4	10	100	1	2	10	80.5	0.99	1.99×10^6	250	0.0005	1.56×10^7
5	100	10	1	2	1	80.5	0.99	1.99×10^5	250	0.004	5890

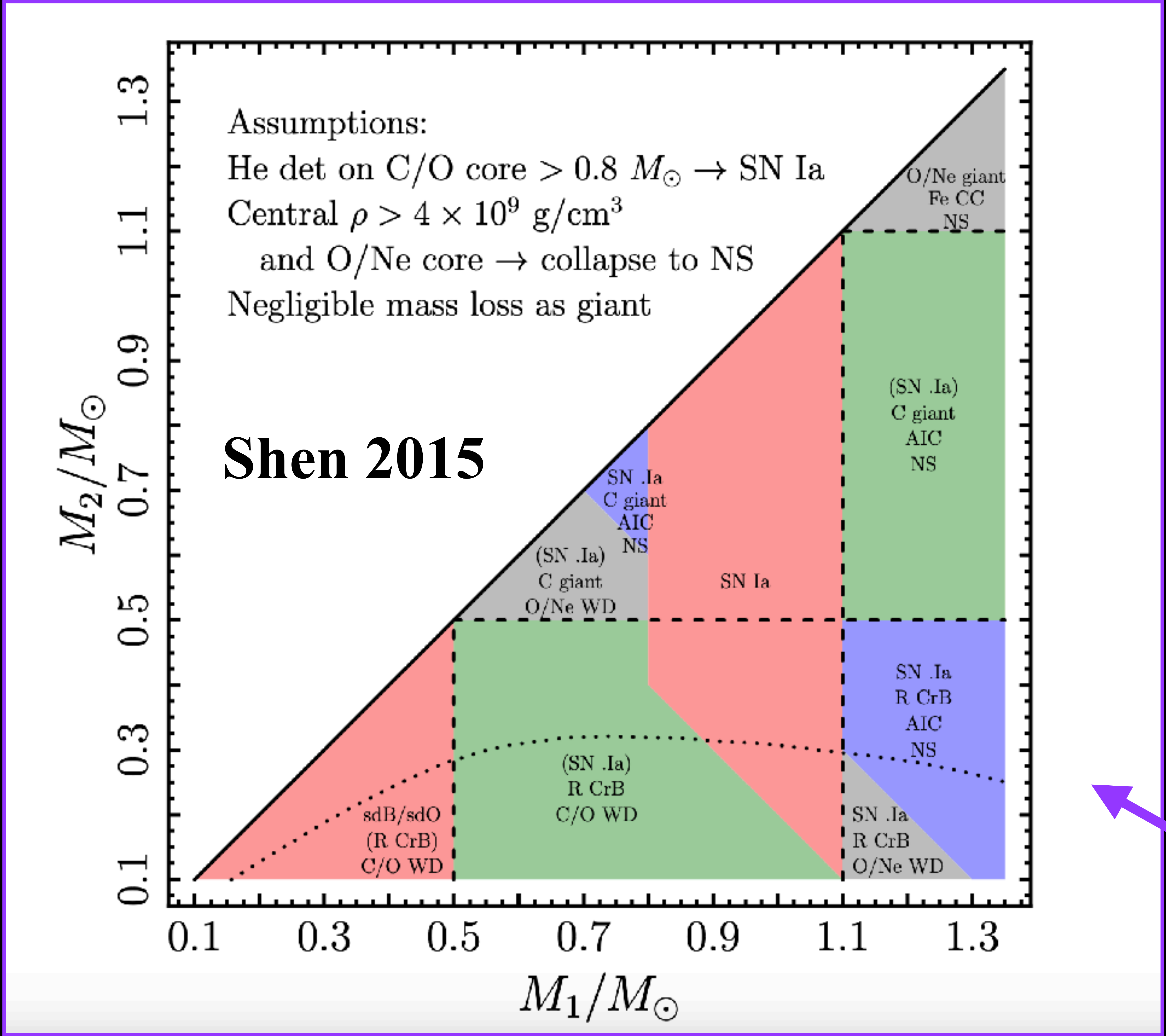
EMRI-FRBs: Cosmic comb and EM signal

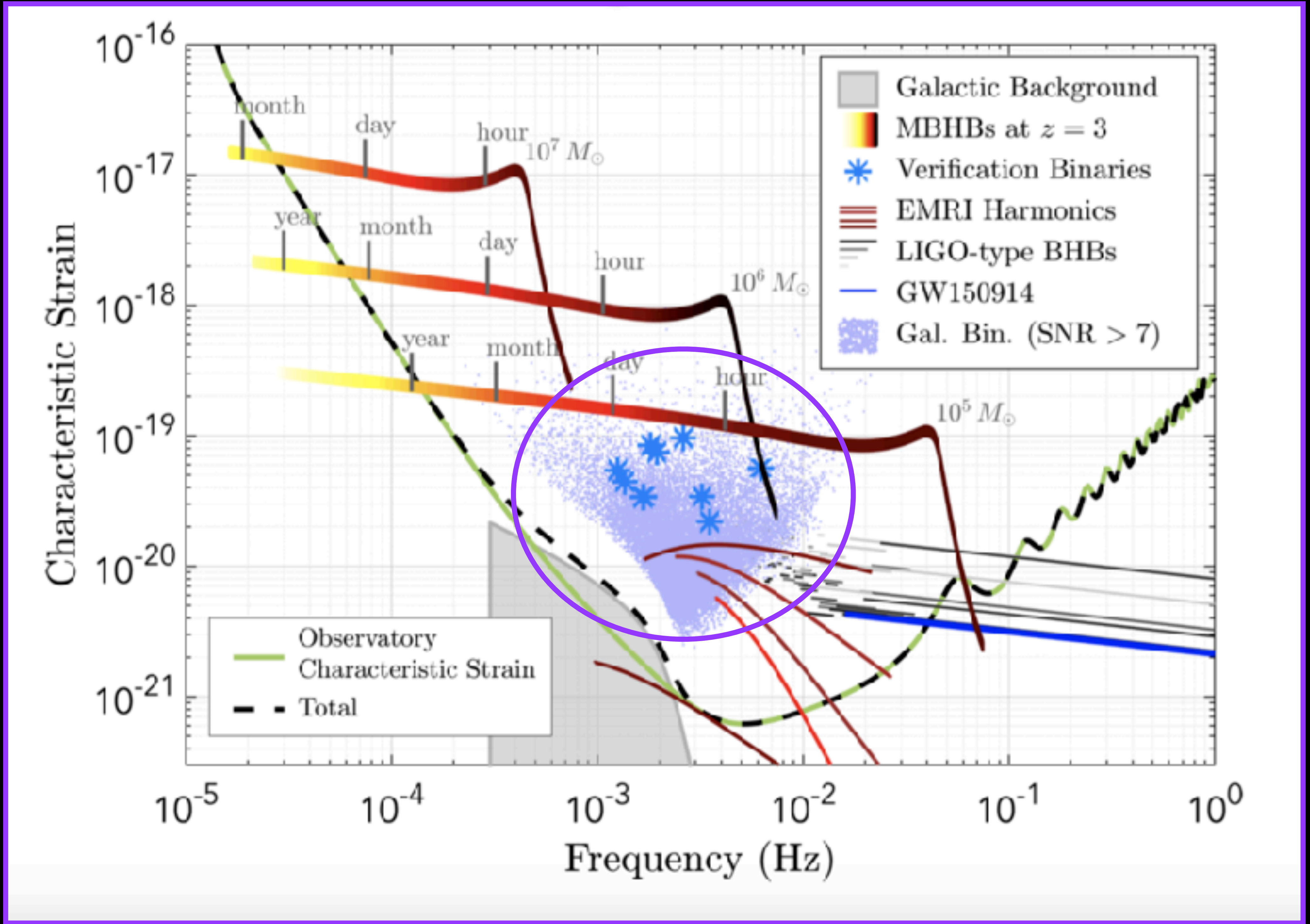


FRB 20190520B; Niu et al. 2022

This model can accommodate repeaters

Binary white dwarf mergers

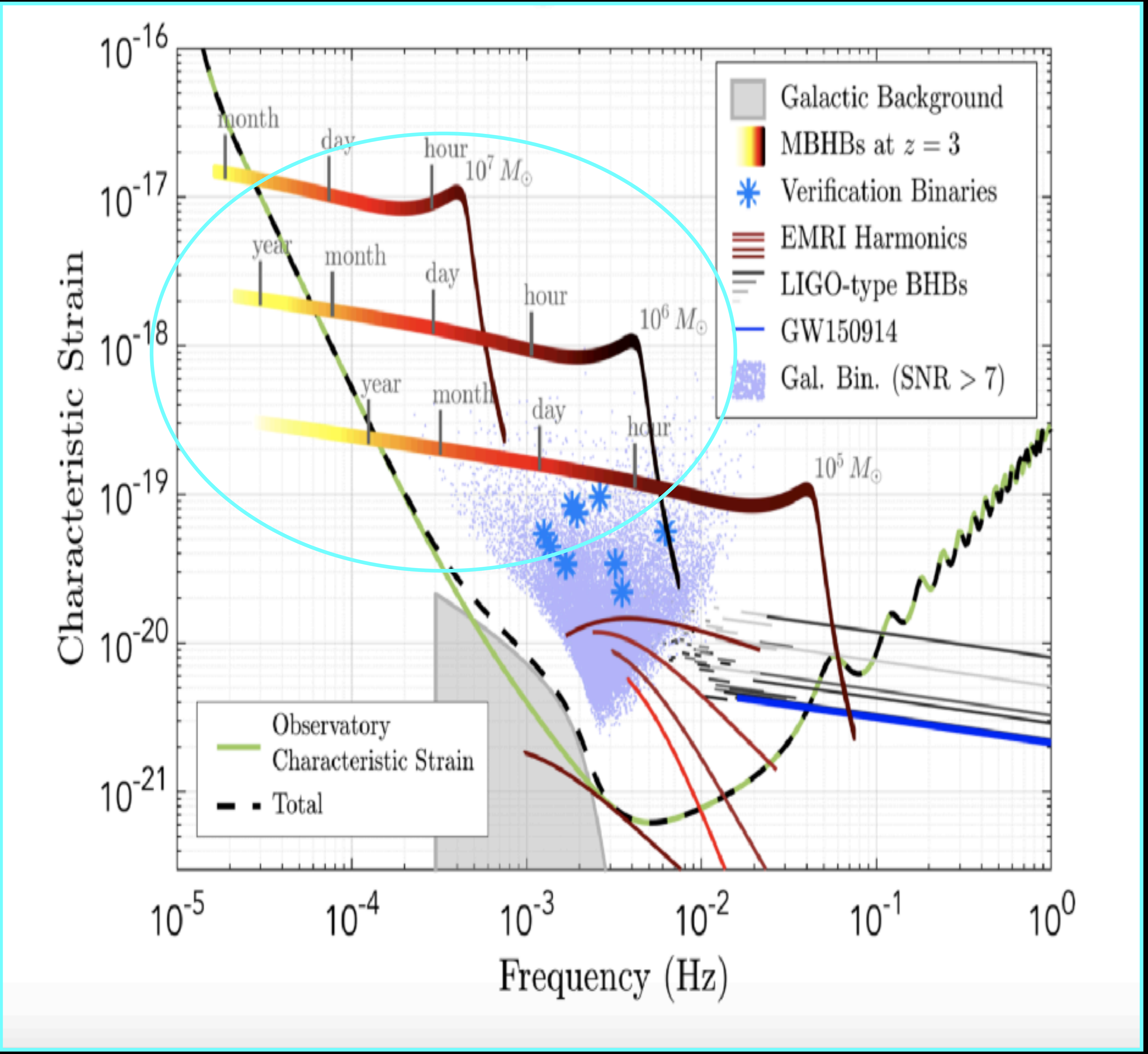




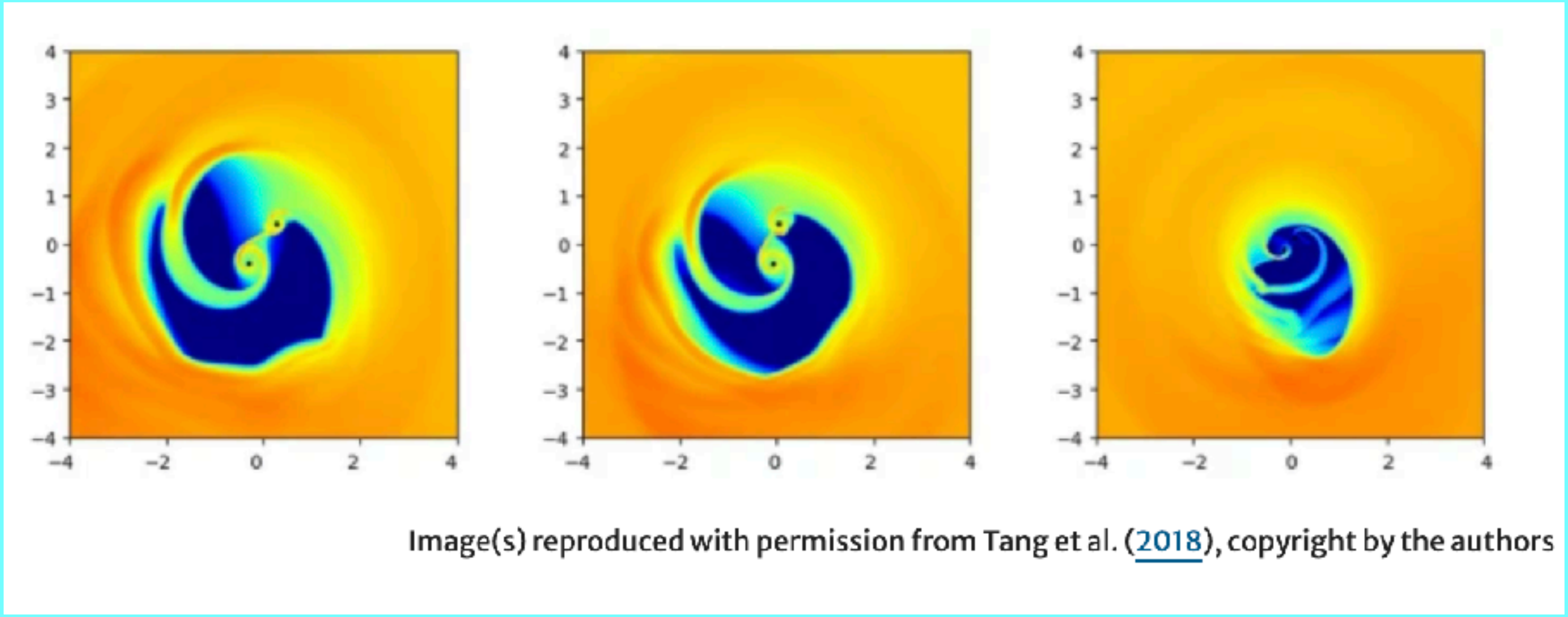
Amaro-Seoane et al. 2017

Many potential EM counterparts depending on mass ratio, tides, mass transfer, etc

IMBH/MBH BINARIES

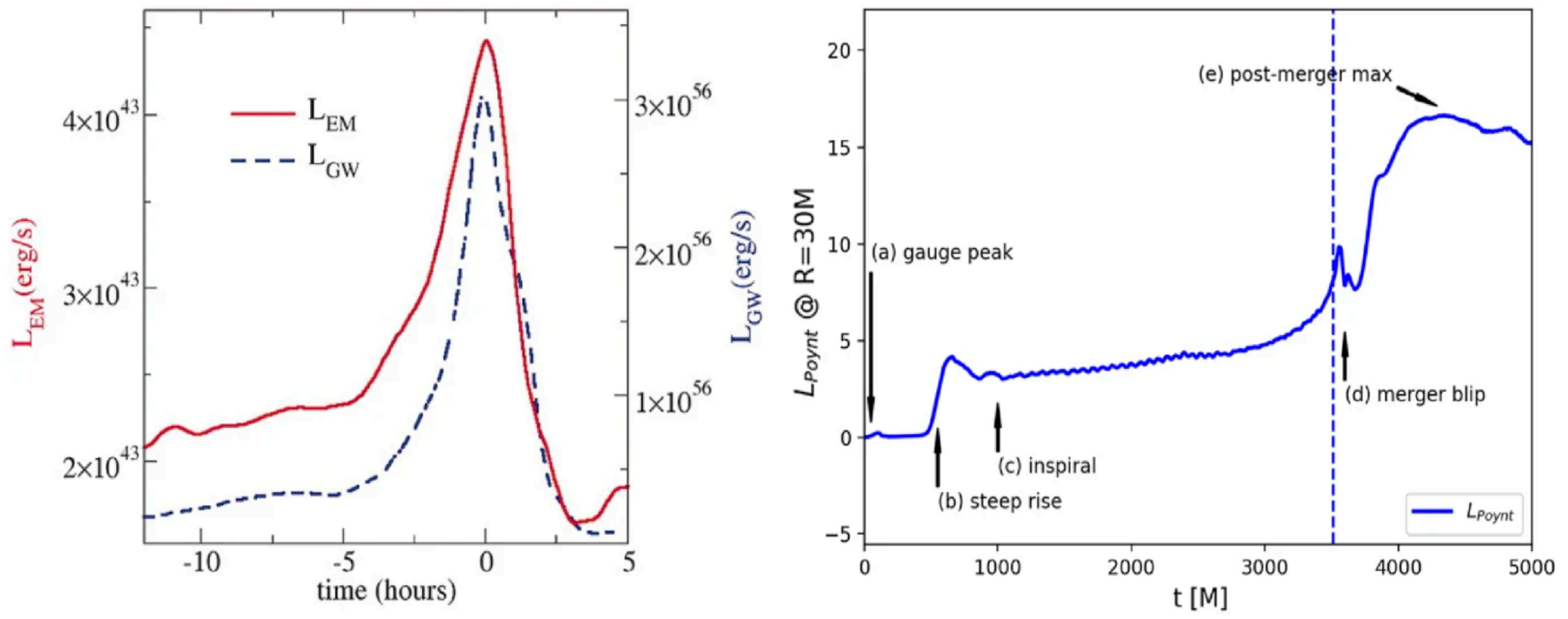


Amaro-Seoane et al. 2017



Surface density around equal mass $M_{BH} = 10^6 M_\odot$ BBH over timescale of ~ 1 week (from Tang et al 2018 reproduced in Bogdanavić et al 2022)

EM SIGNALS FROM MBH BINARIES

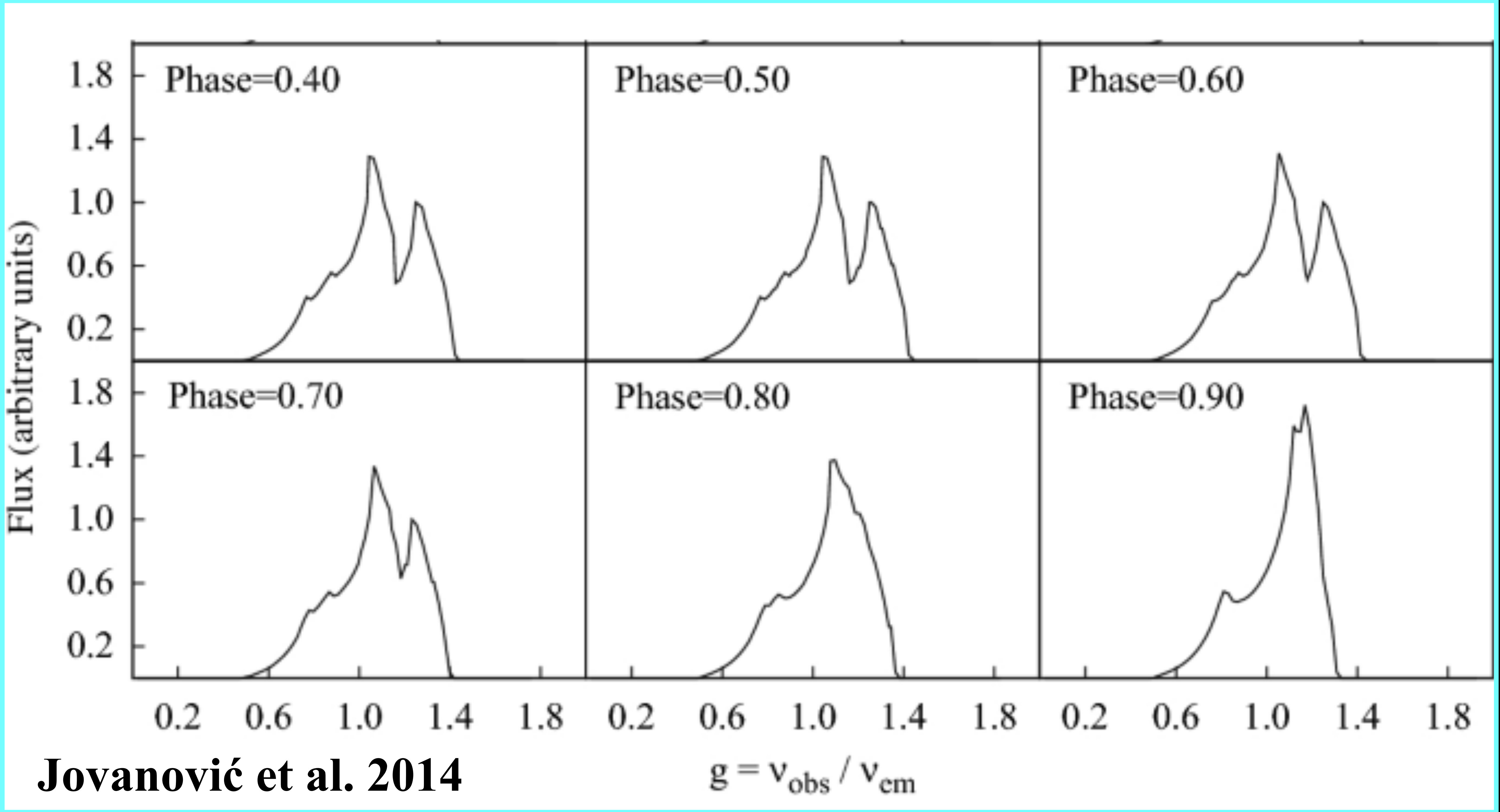


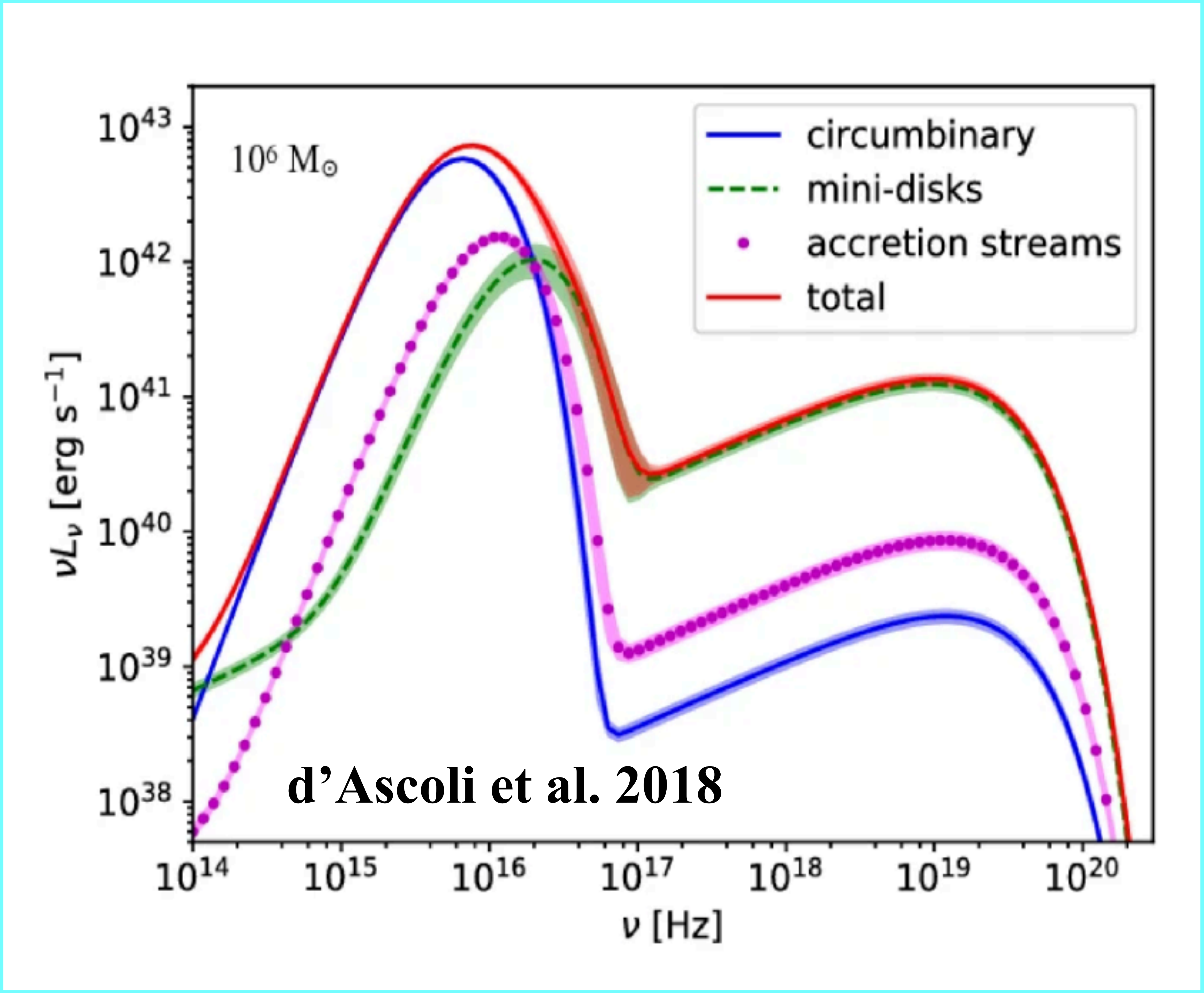
Image(s) adapted from [left] Palenzuela et al. (2010b), copyright by AAAS; and [right] from Kelly et al. (2017), copyright by APS

Poynting Luminosity in near vacuum for merger with $M_{BH} = 10^8 M_{\odot}$, $B = 10^4 G$; Merger at t=0

Poynting Luminosity for merger in radiatively inefficient magnetized gas, $\rho = 10^{-13} g cm^{-3}$; 1t = 0.14hr; 1L= $10^{44} ergs^{-1}$

Em signals from IMBH/MBH binaries

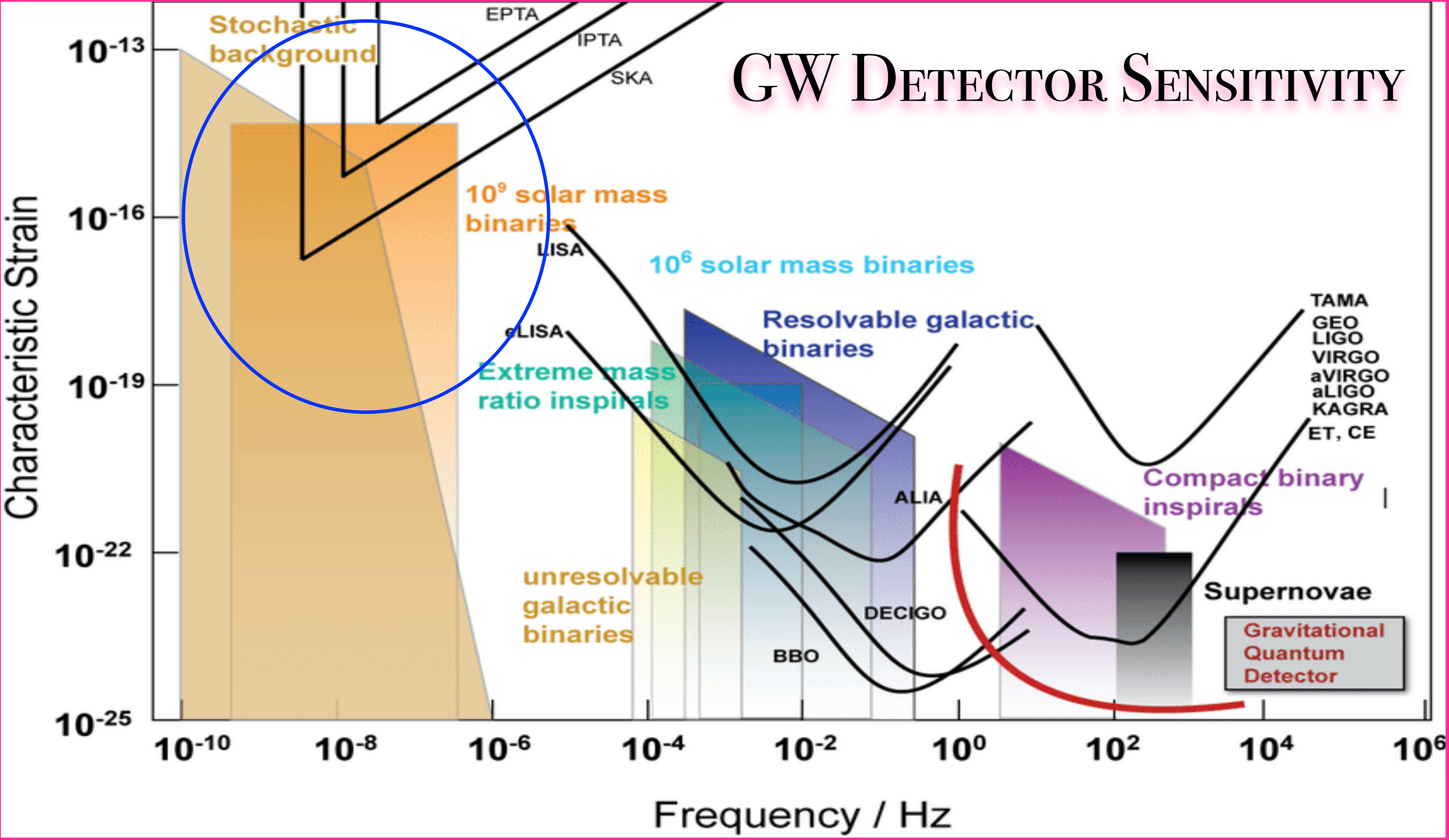




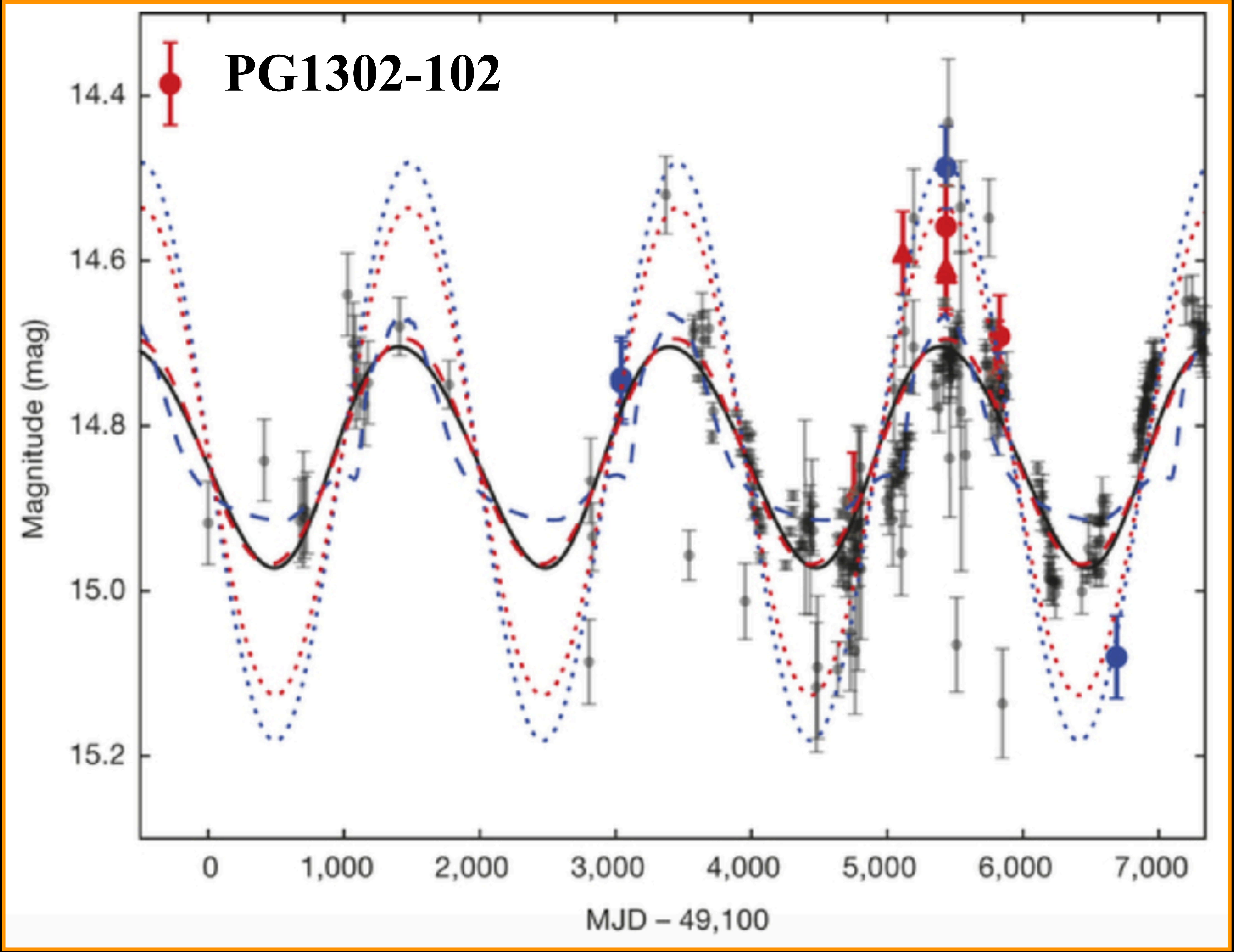
Evolution of iron K-alpha profile for equal mass binary, different orbital phases. Two slowly spinning BH with separation a=2000M, e=0.75.

Spectrum from non-spinning $M_{BH} = 10^6 M_\odot$ BBH, 2nd orbit, initial separation of 20 M, accretion at half Eddington, view is face on

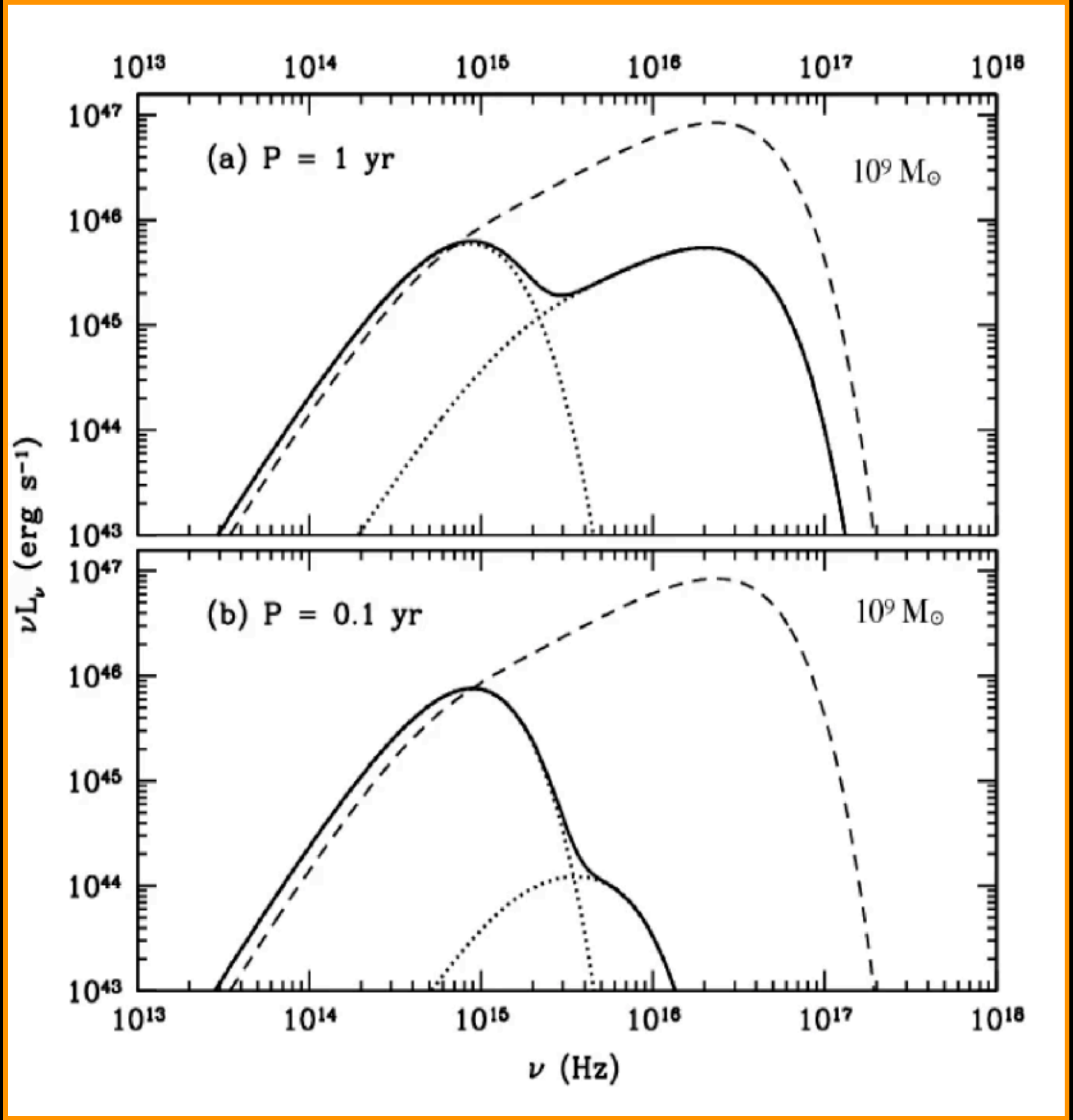
GW Detector Sensitivity



EM SIGNALS FROM SMBH BINARIES



Optical and UV light curve, period ~ 1884 days, $M_{BH} \sim 10^9 M_\odot$; Graham et al. 2015



SMBH binary spectra at different orbital periods (solid line); Tanaka et al. 2012

Next era of GW observatories opens the window to our universe much wider

Novel mechanisms for r-process heavy element production, new mechanisms for FRBs, …

Understanding EM counterparts to the GW emission is necessary to unravelling the physics of our universe

Thank you!

Sim A:
Light r-process

$T_o = 2x10^9 K$

$\xi = 2$

$r = 10^9 cm$

$\tau_1 = \tau_2 = 3.5x10^2 s$

$\epsilon = 2$

$\rho_o = 3.2x10^4 g/cm^3$

$Y_e = 0.334$

Sim B:
Robust r-process

$T_o = 2x10^9 K$

$\xi = 2$

$r = 10^9 cm$

$\tau_1 = \tau_2 = 3.5x10^2 s$

$\epsilon = 28.3$

$\rho_o = 8.9x10^5 g/cm^3$

$Y_e = 0.034$

Sim C:
i-process

$T_o = 0.1x10^9 K$

$\xi = 3.5$

$r = 5.3x10^{11} cm$

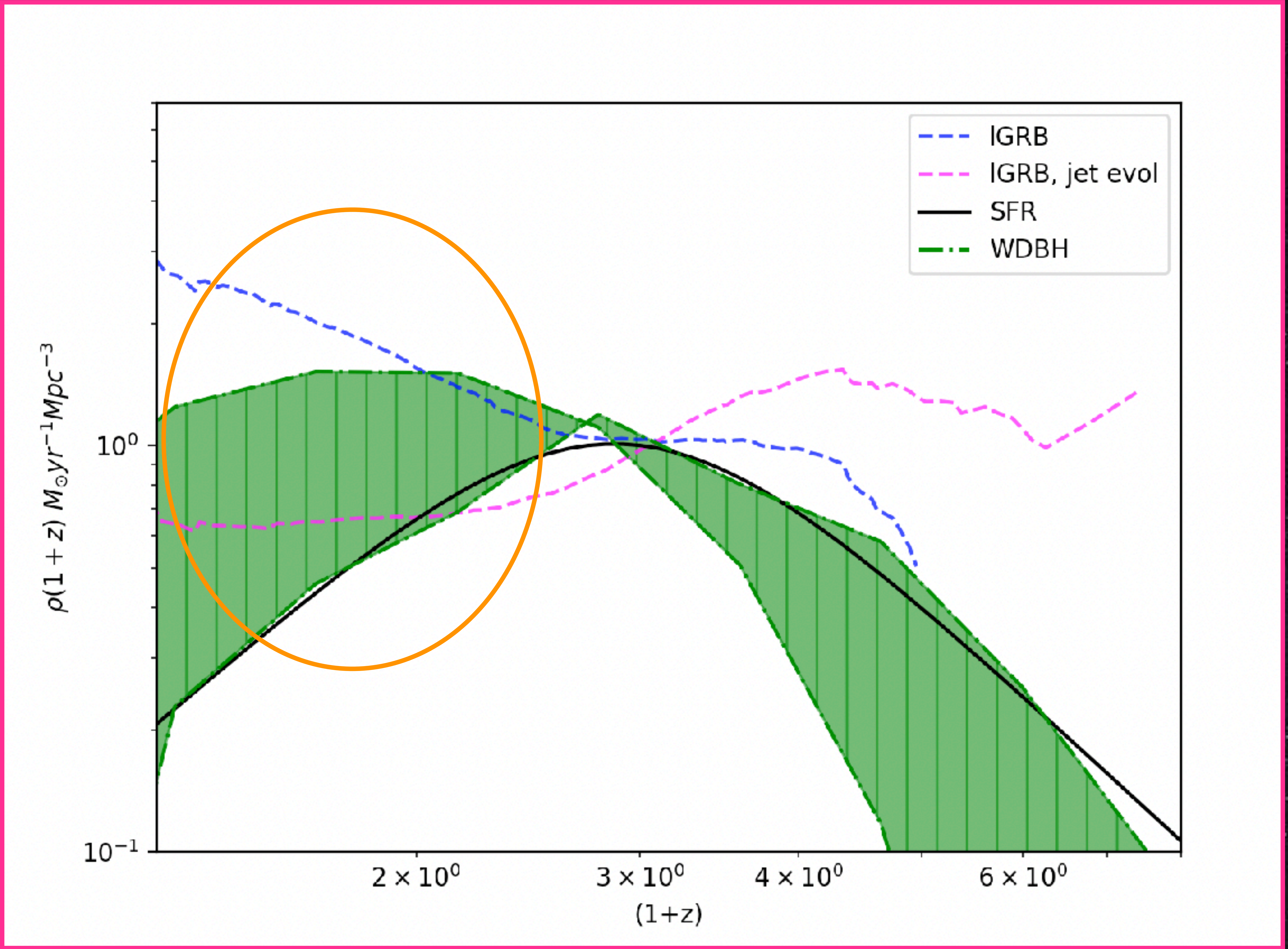
$\tau_1 = \tau_2 = 3.5x10^2 s$

$\epsilon = 282.2$

$\rho_o = 6.5x10^3 g/cm^3$

$Y_e = 0.0035$

Mumpower, Lee, L-R. et al. 2024



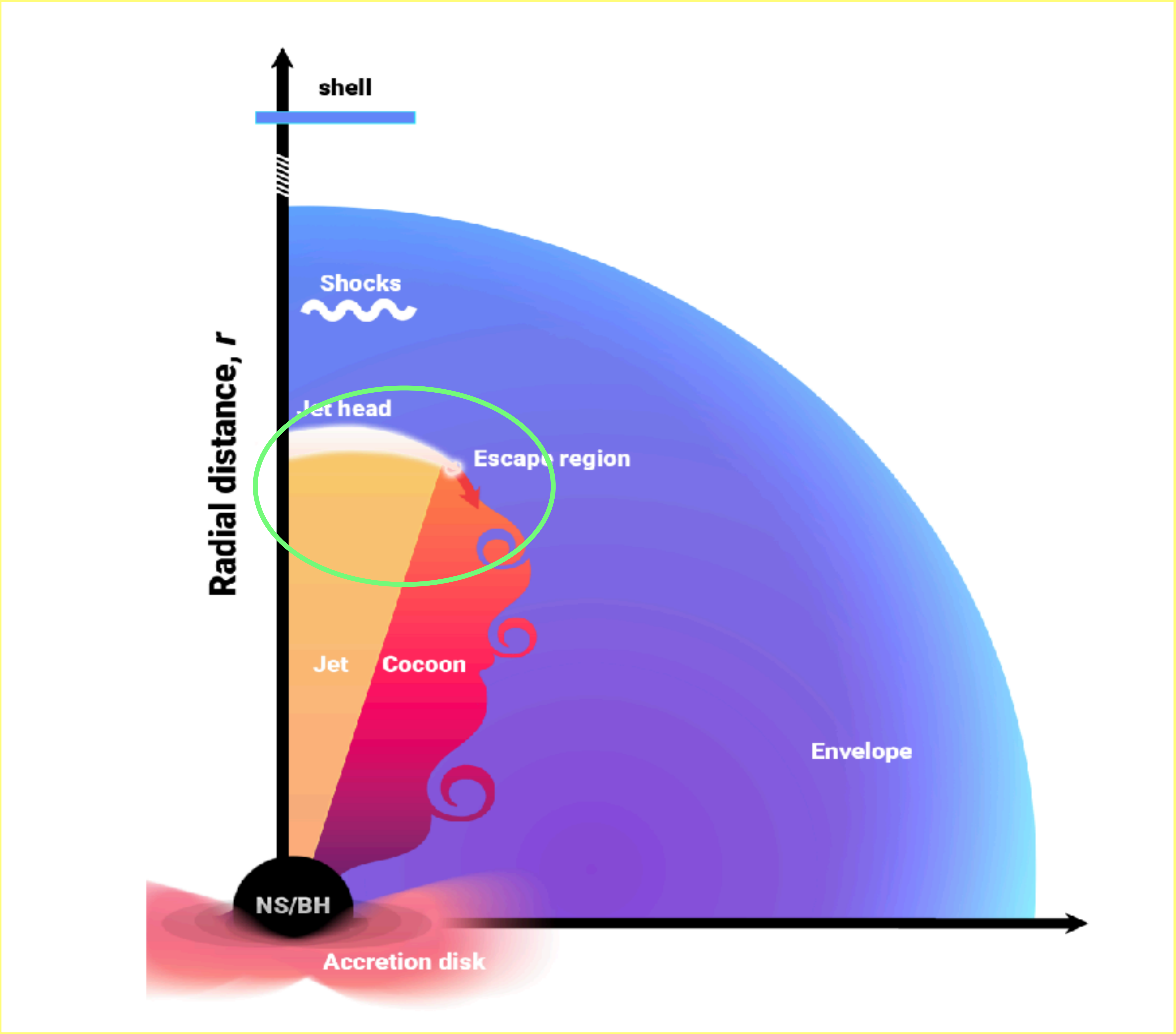
CONTRIBUTION FROM WHITE DWARF-BLACK HOLE MERGERS

L-R et al., 2024

1 H Hydrogen																	2 He Helium
3 Li Lithium	4 Be Beryllium											5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
11 Na Sodium	12 Mg Magnesi...											13 Al Aluminium	14 Si Silicon	15 P Phosph...	16 S Sulfur	17 Cl Chlorine	18 Ar Argon
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Mangan...	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germani...	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton
37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybde...	43 Tc Techneti...	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
55 Cs Caesium	56 Ba Barium	57 La Lanthan...	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
87 Fr Francium	88 Ra Radium	89 Ac Actinium	104 Rf Rutherfo...	105 Db Dubnium	106 Sg Seaborg...	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitneri...	110 Ds Darmsta...	111 Rg Roentge...	112 Cn Coperni...	113 Nh Nihonium	114 Fl Flerovium	115 Mc Moscovi...	116 Lv Livermor...	117 Ts Tenness...	118 Og Oganess...
			58 Ce Cerium	59 Pr Praseod...	60 Nd Neodym...	61 Pm Prometh...	62 Sm Samarium	63 Eu Europium	64 Gd Gadolini...	65 Tb Terbium	66 Dy Dysprosi...	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium	
			90 Th Thorium	91 Pa Protacti...	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californi...	99 Es Einsteini...	100 Fm Fermium	101 Md Mendele...	102 No Nobelium	103 Lr Lawrenc...	

- Alkali metals
- Alkaline earth metals
- Transition metals
- Post-transition metals
- Metalloids
- Reactive nonmetals
- Noble gases
- Lanthanides
- Actinides
- Unknown properties

NEUTRONS FROM HADRONIC PHOTO PRODUCTION IN COLLAPSAR JETS



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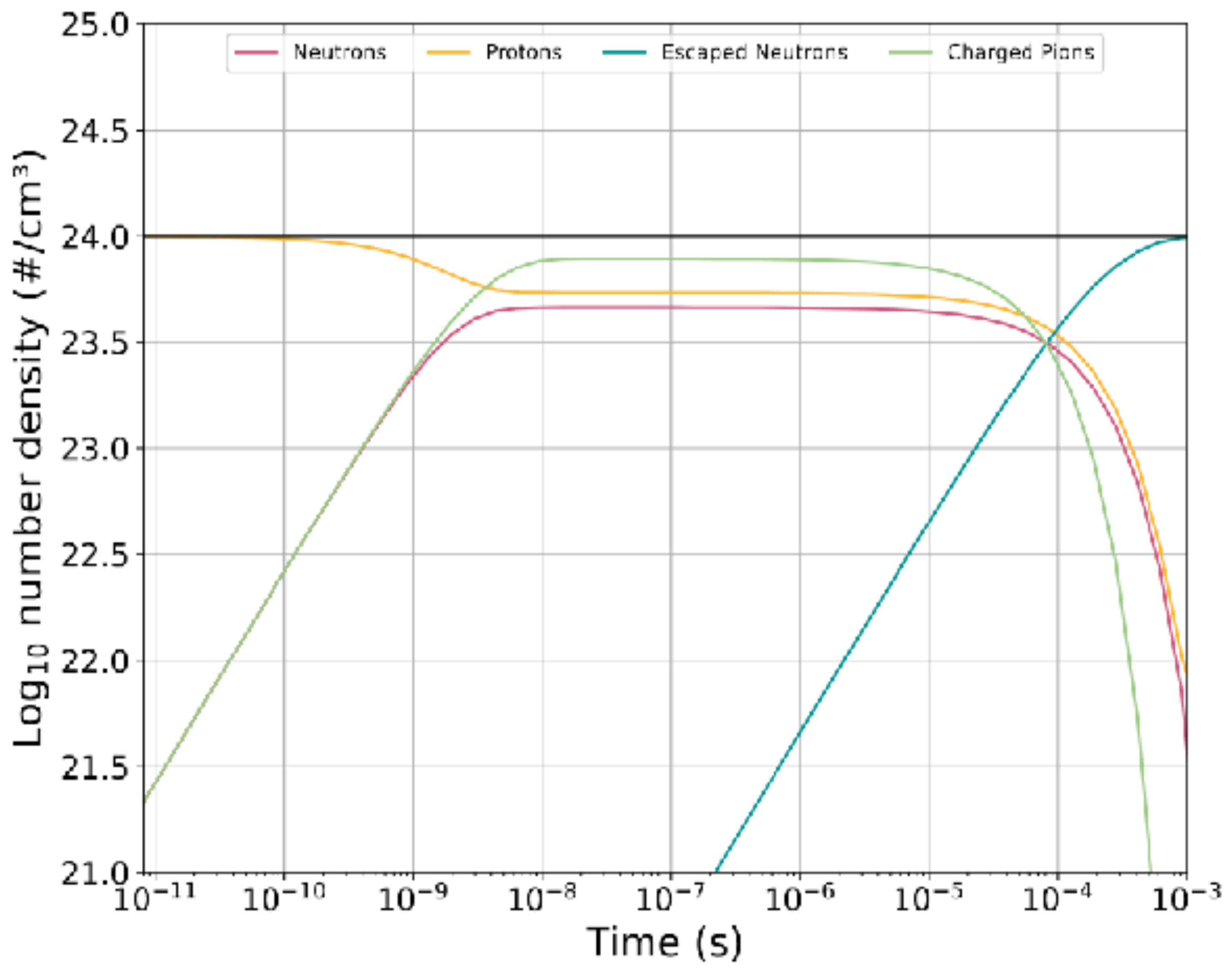

Figure 4. A simplified hadronic reaction network starting with 100% protons (yellow). Neutrons (red) and pions (green) are produced nearly instantaneously. Baryon number is conserved (solid black line), despite neutrons escaping to another zone (blue); Meson number is not a conserved quantity (green).